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Seemann

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[54] **METHOD FOR NON-DESTRUCTIVE INSPECTION OF AN AIRCRAFT**

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Related U.S. Application Data

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[51] **Int. Cl.**[6] **G01B 9/02**

[52] **U.S. Cl.** **356/35.5**; 356/358; 73/802

[58] **Field of Search** 356/4.09, 4.1, 356/35.5, 358; 73/800, 802; 180/164

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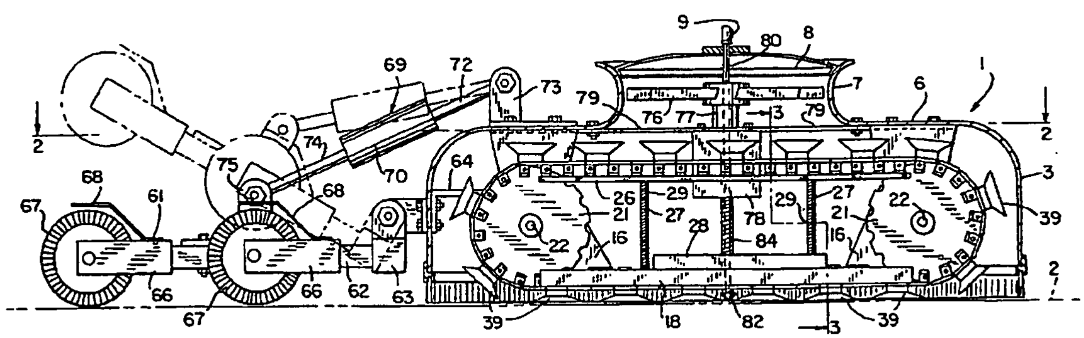
[57] **ABSTRACT**

A robot for performing a working operation on a surface. The robot comprises a frame which supports a pair of parallel tracks. An endless link chain is mounted for travel on each track and each chain is driven by an independent motor mounted on the frame. Each track is provided with at least two recesses with each recess having an open side facing the respective chain. A series of vacuum cups are mounted on each chain and are adapted to engage the surface to be traversed. A first series of ports connect a first recess of each track and a first group of vacuum cups on each chain, while a second series of ports communicate between the second recess of each track and a second group of vacuum cups. A source of vacuum is connected to the recesses and acts through the ports to the respective vacuum cups to enable the vacuum cups to grip the surface. In a preferred manner of use, the robot is employed with a laser tracking system in the non-destructive inspection of an aircraft.

6 Claims, 4 Drawing Sheets



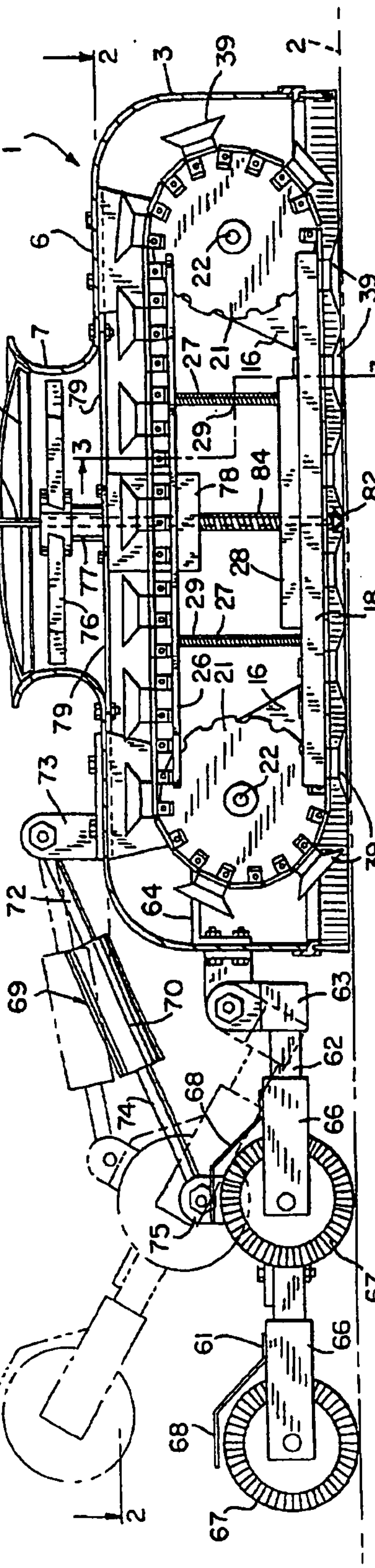


FIG. 1

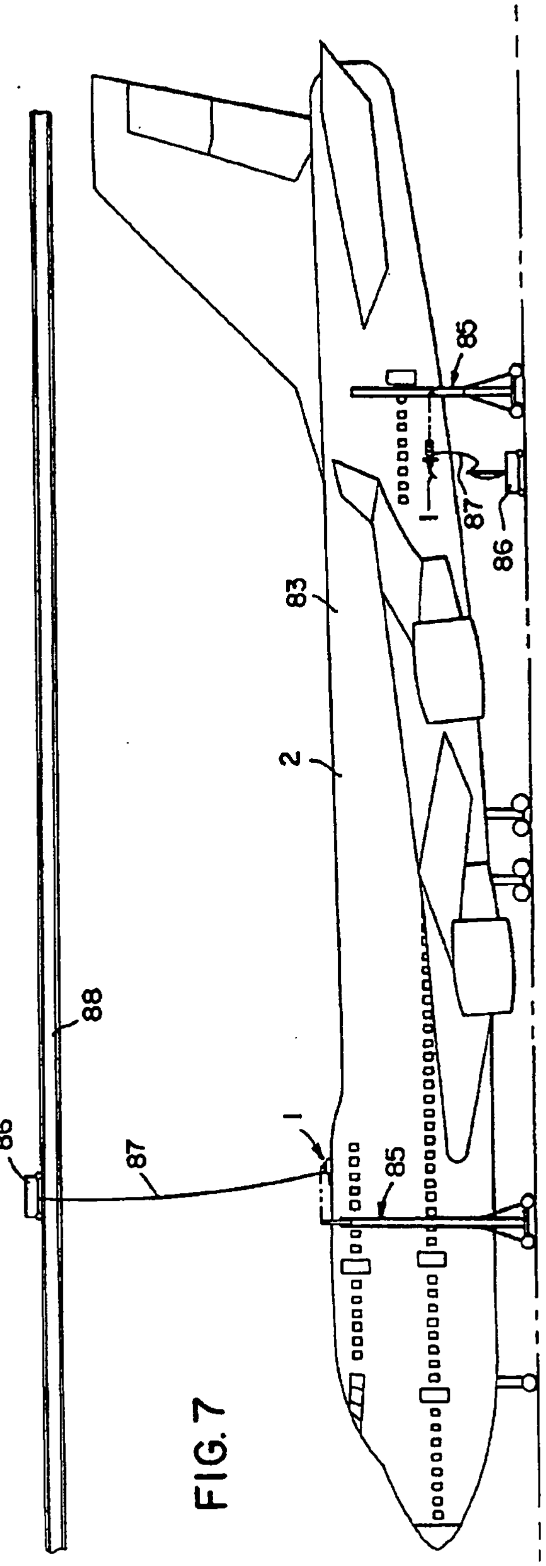


FIG. 7

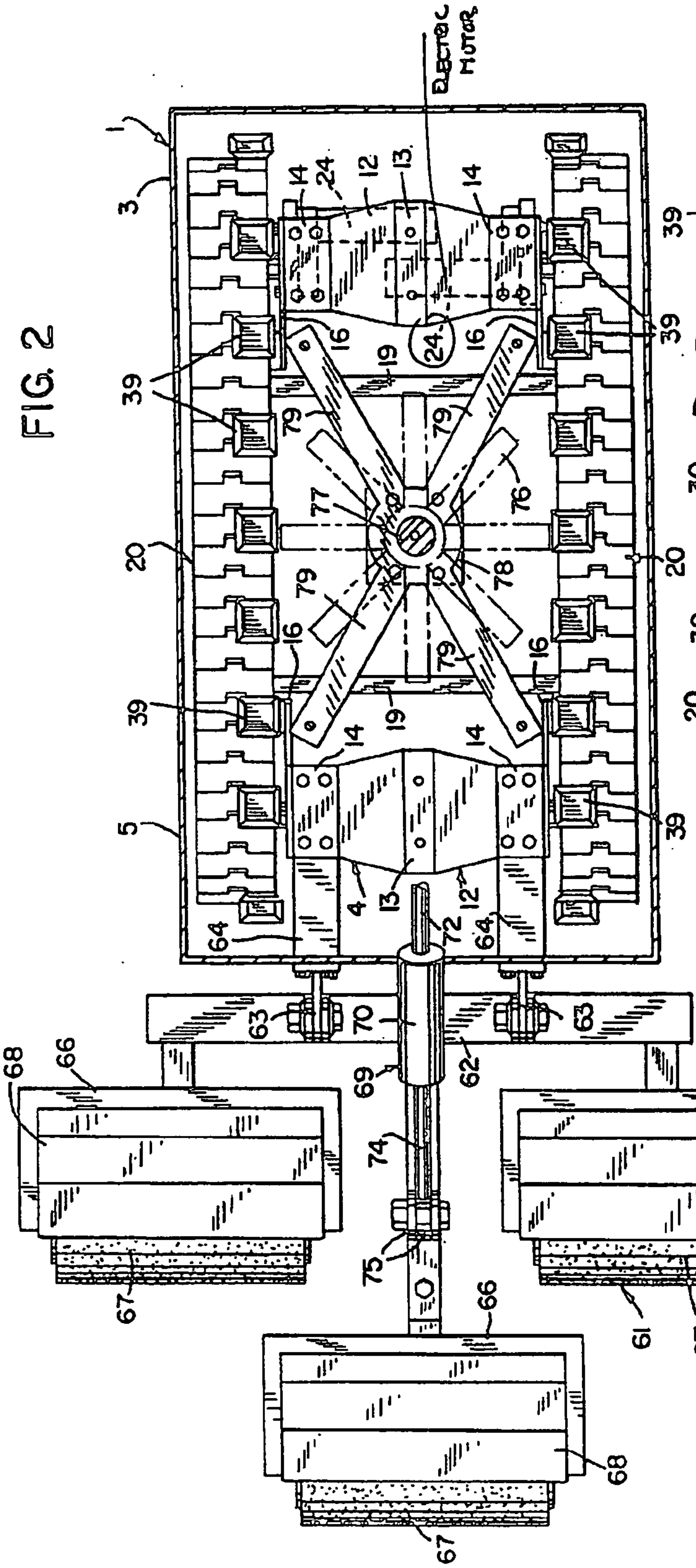


FIG. 2

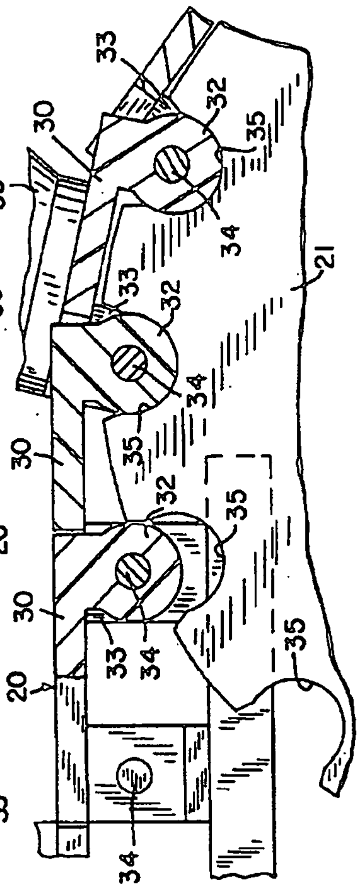
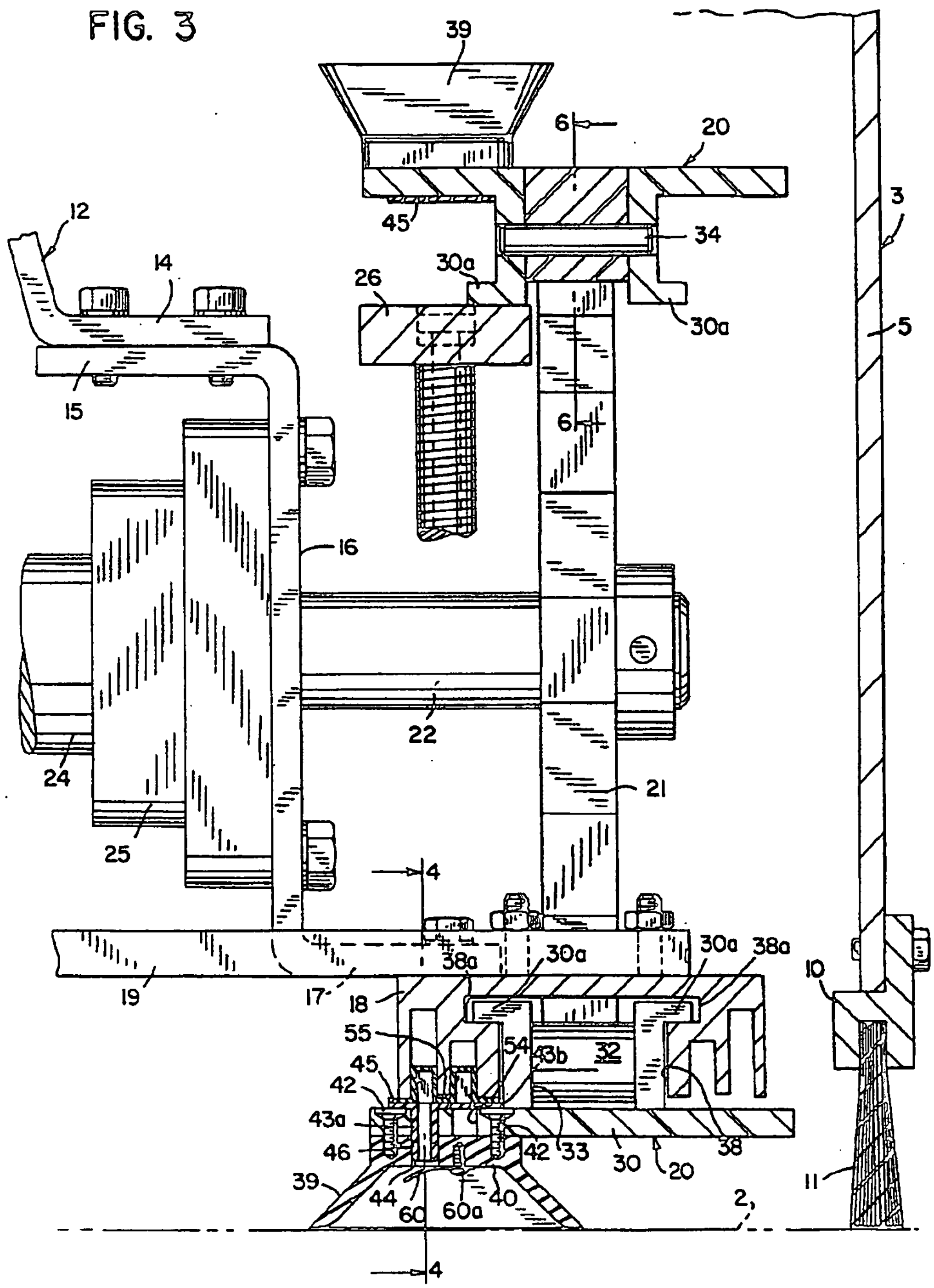


FIG. 6

FIG. 3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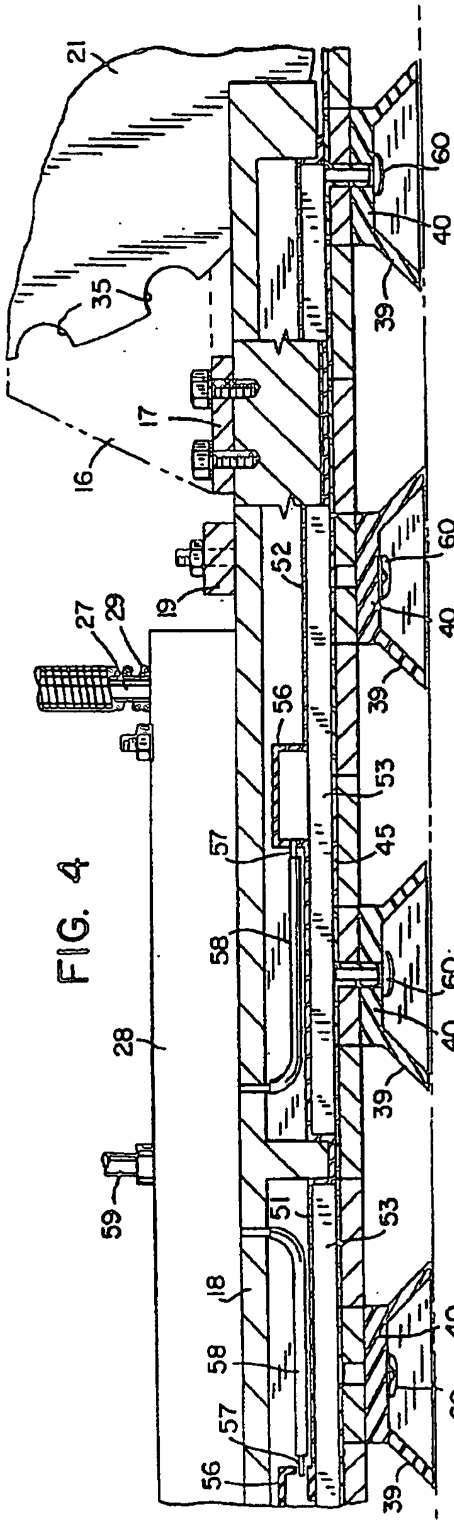
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FIG. 4

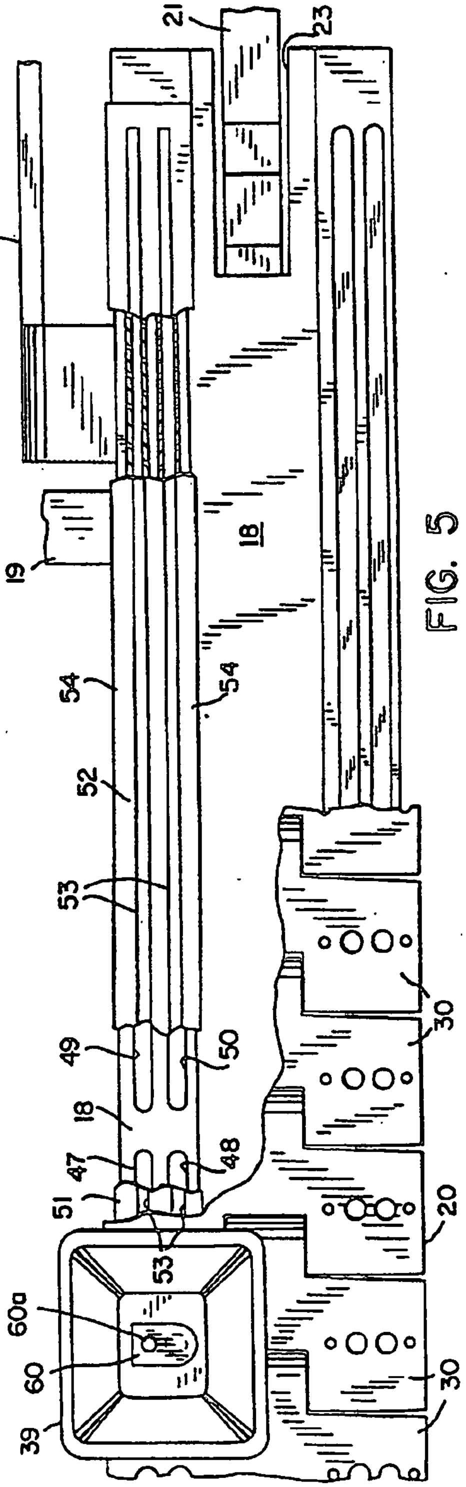
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FIG. 5

METHOD FOR NON-DESTRUCTIVE INSPECTION OF AN AIRCRAFT

This is a division of application Ser. No. 08/063,464, filed May, 18, 1993, now U.S. Pat. No. 5,487,440.

BACKGROUND OF THE INVENTION

Robotic devices have been proposed for performing a working operation, such as cleaning or polishing surfaces, that are not accessible to normal manual operations. In general, the robotic devices have been used on flat or planer surfaces such as windows, building panels and the like. The typical robotic device includes a pair of endless belts or tracks, each carrying a series of vacuum cups. The belts are independently and remotely driven to move the device across the surface to be treated, and a source of vacuum, such as a vacuum pump, is connected to the vacuum cups to create a negative pressure within the cups so that the cups can grip the surface and enable the robotic device to move over inclined or vertical surfaces. A typical robotic device can operate on smooth continuous surfaces but if the device moves across an obstruction or crack in a vertical or inclined surface, the vacuum may be lost, resulting in the device falling from the surface.

Large commercial aircraft are normally washed and waxed every thirty days. Because of the large size and shape of the aircraft it is customary to erect a scaffold along side the aircraft and a number of workers supported on the scaffold then hand scrub the outer surface of the aircraft. After scrubbing, the aircraft is waxed and polished using manual rotary buffers. The buffers are relatively heavy and due to the large surface area of the aircraft a buffing operation is a tedious and time consuming operation. The entire operation of scrubbing, waxing and buffing the aircraft usually takes a period of 20 to 30 hours utilizing 10 workers.

Commercial aircraft are also subjected to a non-destructive inspection after 7,000 cycles of pressurization. Each take-off and landing in which the aircraft is pressurized is considered to be a pressurization cycle. In the typical non-destructive inspection, the paint is stripped entirely from the aircraft and the seams and rivets are manually inspected. If a defect is observed during the inspection, the area of the defect is marked and is subjected to an eddy-current sensor to determine the magnitude of the defect. After the manual inspection the aircraft is repainted and subsequently waxed and buffed.

The normal paint stripping, inspecting, repainting and waxing operation is extremely time-consuming and labor intensive, resulting in a substantial expenditure. As a further problem the paint stripping operation presents a serious environmental problem, in that methylene chloride is generally used as the solvent to remove the paint and for a large aircraft, such as a Boeing 747, upwards of 1,000 gallons of methylene chloride may be required to strip the paint from the aircraft. As methylene chloride is toxic and presents an environmental problem, pollution abatement equipment is necessary in order to remove the solvent fumes from the paint stripping area.

SUMMARY OF THE INVENTION

The invention is directed to a robotic device for performing a working operation on a surface and has particular application to performing a working operation on a contoured surface having surface irregularities such as encountered in a commercial aircraft.

The robotic device comprises a supporting structure or frame which supports an outer open bottom housing or hood.

A pair of flexible tracks are mounted on the frame and an endless member, such as a link chain, is mounted for travel on each of the tracks. Each chain in independently driven by a separate motor which is mounted on the frame.

Each of the tracks is formed with at least two channels with each channel having an open side facing the respective chain. A series of vacuum cups are mounted on each chain and a series of first ports are connected between a first of the channels of each track and a first group of vacuum cups, while a second series of ports provide communication between a second channel of each track and a second group of vacuum cups. The first and second groups of vacuum cups are preferably in alternating sequence.

Negative pressure or a vacuum is applied to each channel and hence through the ports to the vacuum cups, thus enabling the cups to grip a surface to be traversed.

In a preferred form of the invention, each track is formed with two pair of side-by-side channels and the vacuum is applied independently to all four channels. In this embodiment, a first series of ports in the chain register with the first and third channels, while a second series of ports in the chain register with the second and fourth channels. As the vacuum is applied independently to the several channels, the robotic device can move over gaps or obstructions in the surface without losing vacuum in all of the vacuum cups. If for example, the device moves over a crack causing a loss of vacuum in one of the track channels, the vacuum will be retained in the remaining channels to thereby maintain the device in gripping contact with the surface.

In a preferred embodiment the robotic device is employed for non-destructive inspection of aircraft using a laser tracking system. In this embodiment one or more laser units are mounted on the ground adjacent the air-craft and a retro-reflector or cats-eye is mounted on a support carried by the robotic device. The support is slidable relative to the robotic device and is biased downwardly so that a shoe or sensor carried by the support will ride against the surface of the aircraft. As the robotic device moves in the desired path of travel over the aircraft surface, the sensor or shoe rides on the surface, and through the laser tracking system, the surface of the aircraft is mapped. The aircraft is then pressurized and the surface is again mapped and any surface deviations, outside of a given tolerance, indicate possible defects in the aircraft surface.

The use of the robotic device along with the laser tracking system, to provide non-destructive inspection of a aircraft, eliminates the manual paint stripping, visual inspection, repainting and waxing of the aircraft as is normally used and therefore substantially reduces the overall time and cost of the non-destructive inspection. As a further advantage, the method of the invention eliminates the use of toxic solvents which are normally used to strip the paint from the aircraft and correspondingly eliminates the pollution control devices that are necessary with the use of such solvents.

In a second embodiment of the invention the robotic device can be employed to move a working implement over the aircraft of other surface. The working implement can be a rotary scrubber, buffer, paint sprayer, or the like. By utilizing the robotic device to perform these working operation the extensive hand labor normally required to wash, wax and or paint an aircraft or other surface is substantially reduced. As a further advantage, a robotic device enables a constant application of pressure to be applied through the implement to the surface thus providing a more uniform cleaning and polishing operation.

The invention also can include a safety feature to prevent the robotic device from falling from the surface in the event

of failure of the vacuum system. In this regard, a fan is mounted in an opening or aperture in the outer housing and if the magnitude of the vacuum drops beneath a preselected valve, the fan is operated to create a negative pressure within the outer housing or hood to prevent the robotic device from falling from the surface.

The robotic device of the invention has the advantage that it is capable of moving over surface deviations, such as obstructions or gaps without losing vacuum. Moreover the frame is composed of flexible plastic material which enables the robotic device to follow the curved contour of an aircraft or other surface to be treated.

Other objects and advantages will appear during the course of the following description.

DESCRIPTION OF THE DRAWINGS

The drawings illustrate the best mode presently contemplated for carrying out the invention.

In the drawings

FIG. 1 is a longitudinal section of the robotic device of the invention;

FIG. 2 is a section taken along line 2—2 of FIG. 1;

FIG. 3 is a section taken along line 3—3 of FIG. 2 and showing the connection of the drive to one of the chains;

FIG. 4 is an enlarged fragmentary longitudinal section taken along line 4—4 of FIG. 3 and showing the vacuum connection the vacuum cups;

FIG. 5 is a bottom view of the track with parts broken away;

FIG. 6 is an enlarged fragmentary longitudinal section showing the engagement of the chain with a drive sprocket; and

FIG. 7 is a schematic view showing the use of the robotic device along with a laser tracking system in the non-destructive inspection of an aircraft.

DESCRIPTION OF THE ILLUSTRATED EMBODIMENT

FIGS. 1–6 show a robotic device 1 that can be employed to provide a working operation on a surface 2. Surface 2 can either be a planer or non-planer surface, such as an aircraft, building, bridge, storage tank, train or the like.

Robotic device 1 includes an outer open bottom housing or hood 3, which is supported by an internal frame 4. Housing 3 is composed of a rectangular side wall 5 and a generally flat upper surface or top 6, having an opening therein which is bordered by a generally curved upwardly extending flange 7. A series of braces 8 extend diametrically across the opening in flange 7 and support a retro-reflector or cats-eye 9 to be used in a laser tracking system, as will be hereinafter described.

Secured to the lower edge of sidewall 5 is a strip 10 having a downwardly facing groove which receives the upper edge of a brush seal 11, as shown in FIG. 3. Brush seal 11 includes a plurality of fine, synthetic, flexible bristles formed of a material such as nylon which engage the surface 2 and provide a seal to the surface.

Frame 4 consists of a pair of inverted V-shape frame members 12 which extend transversely of the housing 3 and each frame member 12 includes an upper flat section 13, which is secured to the under surface 6 of housing 3. In addition, each frame member 12 is provided with a pair of lower, horizontal flanges 14 and each flange 14 is secured to the upper flange 15 of a bracket 16, as best shown in FIG. 3. With this construction there are four brackets 16 with a pair of the brackets being located along each side of the device.

Each bracket 16 also includes a lower flange 17 which extends outwardly and is secured to the upper surface of a flexible track or guide 18, as seen in FIG. 3. Each track 18 is preferably formed of plastic material and is connected between a pair of the brackets 16. In addition, a pair of braces 19 extend transversely of the device and connect the tracks 18 together.

Tracks 18 serve to guide the lower run of an endless link chain 20 as shown in FIG. 3.

To drive the chains 20 in their endless paths of travel, a sprocket 21 is mounted for rotation outwardly of each bracket 16 and the sprockets on each side of the frame are engaged with the respective chain. Each sprocket 21 is carried by a shaft 22 which extends outwardly from the respective bracket 16, as shown in FIG. 3. The ends of each track, as illustrated in FIG. 5, are provided with longitudinal, open-ended slots 23 which receive the respective sprockets 21.

One sprocket of each longitudinal pair is an idler sprocket, while the other sprocket 21 of each longitudinal pair is a driven sprocket. To drive the sprockets 21*b*, an electric motor 24 is located inwardly of the bracket 16 and operates through a gear box 25 with the output shaft of the gear box connected to the shaft 22 of the driven sprocket 21. A separate motor 24 is utilized with each driven sprocket 21. Thus operation of the motors 24 acting through the sprockets 21 will drive the respective chain 20 to move the robotic device in the desired path of travel along the surface 2.

As best seen in FIG. 1 the upper run of each chain 20 is supported on a guide bar 26. A pair of rods 27 extend downwardly from each guide bar 26 and the lower end of one of the rods is connected to the respective track 18, while the lower end of the second rod is connected to a manifold block 28, which is mounted on the track 18. Coil springs 29 are located about the rods 27 and urge the guide bar 26 upwardly thereby acting to tension the chain 20.

The construction of each link chain 20 is best illustrated in FIGS. 3, 5 and 7. Each chain 20 is composed of a series of pivotally interconnected links 30 and a boss or tubular projection 32 extends outwardly from one side of each link 30 and is received within a flanged recess 33 in the adjacent link. Pins 34 provide a pivotal connection between the boss 32 of one link and the hinged recess 33 of the adjacent link. The hinged bosses 32 are adapted to be engaged by notches 35 in the respective sprockets 21, as best seen in FIG. 6.

As shown in FIG. 3, the hinged connections 32 of chain 20 are guided for movement within a central groove 38 in track 18 and each chain link is provided with a pair of outwardly extending ears or flanges 30*a* which are received within guideways 38*a* in the track. The engagement of flanges 30*a* with guideways 38*a* prevents downward displacement of the chain 20 from track 18.

A series or row of vacuum cups 39 are mounted on the outer surface of each chain 20, as shown in FIG. 3. The base 40 of each cup 39 is secured by screws 42 to the chain links 30. Each chain link 30 is provided with a pair of side-by-side holes 43*a* and 43*b*, and one of the holes 43*a* registers with a hole 44 in the base 40 of the vacuum cup 39.

Mounted on the upper surface of chain 20, as shown in FIG. 3, is a flexible plastic belt 45. A series of tubes 46 are formed integrally with the belt and project through the aligned holes 43 and 44 in chain links 30 and vacuum cup 39, as shown in FIG. 3. One group of vacuum cups 39 have

holes **44** aligned with holes **43a**, while a second group of vacuum cups have holes **44** aligned with holes **43b**. Preferably the two groups of vacuum cups are in alternating sequence. Accordingly, the tubes **46** are staggered and are inserted within the aligned openings **43a** and **44**, or **43b** and **44**.

The surface of each track **18** facing chain **20** is formed with four grooves or recesses **47**, **48**, **49** and **50**. As seen in FIG. **5**, grooves **47** and **48** are in side-by-side relation and grooves **49** and **50** are in side-by-side relation and are spaced longitudinal from grooves **47** and **48**.

A flexible trough or channel member **51** is mounted within grooves **47** and **48**, and similarly a flexible channel member or trough **52** is mounted in grooves **49** and **50**. Each channel member **51** and **52** includes a pair of side by side channels **53** and the channels **53** of channel member **51** are located within grooves **47** and **48**, while the channels **53** of channel member **52** are located within grooves **49** and **50**. Each channel member **51** and **52** is provided with a flexible peripheral lip **54** which is engaged with and rides against of belt **45**, as shown in FIG. **3**, thus providing a seal between the channels and the belt.

The channel members **51** and **52** are urged in a direction toward the respective chain **20** by a waffle spring **55** which is located between the central portion of each channel member and the lower surface of the track **18** as seen in FIG. **3**.

As best illustrated in FIG. **4**, a block **56** is formed integrally with the upper surface of each channel member **51** and **52**, and a nipple **57** extends outwardly from each block. Each nipple is connected through an internal passage in block **56** with the interior of the respective channel **53**. Tubes **58** connect nipples **57** to manifold block **28** which is mounted on the track **18**. A source of negative pressure or vacuum, such as a vacuum pump, is connected through conduit **59** to manifold **28** and through suitable valving in the manifold the negative pressure is applied through tubes **58** to the four channels **53**. The negative pressure is then applied from each channel **53** through tube **46** in belt **45** to the corresponding vacuum cups **39**. The use of the multiple channels **53**, each being individually connected to a source of vacuum, prevents the entire loss of vacuum to the robot if the robot should traverse an obstruction, crack or other surface deviation. For example, if the robot should move longitudinally over an elongated crack with the crack being aligned with the grooves **47** and **48**, the vacuum in the channels **53** located in grooves **47** and **48** may be lost, but the vacuum will be retained in the channels **53** located in the grooves **49** and **50**, thus preventing the robot from falling from a vertical or inclined surface. Similarly, if the robot should move across a transverse crack the vacuum may be lost in a pair of side-by-side channels **53**, but the other pair of side by side channels will retain the vacuum to maintain the robot in contact with the surface.

In addition, a flexible valve member **60** is connected by screw **60a** to the base **40** of each vacuum cup **39** and is in registry with hole **44**. Valve member **60** is contoured so that it is normally open, as shown in FIG. **3** to permit vacuum to be drawn in cup **39**. However, if cup **39** should travel over a crack or obstruction in surface **2** causing air to enter the cup, the pressure differential will move valve member **60** to a closed position relative to hole **44** to prevent the air entering cup **39** from flowing to the manifold block **28**.

The robotic device, as illustrated in FIGS. **1** and **2**, can be used to move a working implement or attachment **61** across the surface **2** to be treated. The attachment **61** includes a frame **62**, which is pivotally connected to a pair of lugs **63** that extend rearwardly from generally L-shaped brackets **64**, that are connected to the rear frame member **12**, as best in FIG. **2**. Three yokes **66** are connected to frame **63** and a rotary buffer **67** is mounted for rotation in each yoke **66**. The buffers **67** are designed to be individually rotated by drive motors located internally of the buffers, not shown. Suitable shields **68** are connected to the yokes and extend partially over the buffers **67** to confine spray from the buffers.

The buffers **67** are urged downwardly into contact with surface **2** by an air cylinder unit **69**. Cylinder unit **69** includes a cylinder **70** and a rod **72** is connected to one end of the cylinder and is pivotally connected to a pair of lugs **73** which project upwardly from housing **3**. A piston is slidable within cylinder **70** and a piston rod **74**, which is connected to the piston, extends from the opposite end of the cylinder and is pivotally connected to lugs **75** that extend upwardly from frame **62**. By extending cylinder unit **69**, down pressure can be applied through buffer **67** to surface **2**. By retracting the cylinder unit **69**, the frame **62** and buffers **67** can be pivoted upwardly out of contact with surface **2**, as shown by the dashed lines in FIG. **1**.

While the drawings illustrate the working implements to take the form of rotary buffer **67**, it is contemplated that various types of working implements can be substituted, such as scrubbers, waxers, paint applicators and the like.

As a feature of the invention, a provision is incorporated to prevent the robot from falling from a vertical or inclined surface **2** in the event there is a failure in the vacuum system. In this regard, a fan **76** is mounted in the opening in flange **7** which extends upwardly from housing **3**. Fan **76** includes a hollow vertical shaft **77** which is driven by a motor **78**. Motor **78** is supported within the opening in flange **7** by a series of diametrically extending braces **79**.

A sensor, not shown, will sense the magnitude of the vacuum or negative pressure in the vacuum system. If the vacuum decreases to a pre-selected value, the fan **76** will be operated to create a negative pressure within the housing **3** to prevent the robot from falling from surface **2**. The brush seal **11** which is mounted on the peripheral edge of the housing **3** and is engaged with the surface **2**, cooperates with the fan to enable a negative pressure to be created within the housing.

FIG. **7** illustrates a preferred embodiment of the invention in which the robot **1** is utilized for non-destructive inspection of an aircraft. In this embodiment, the retro-reflector or cat's eye **9** is mounted on the upper end of a rod **80** that is slidable within the hollow fan shaft **77**. The lower portion of rod **80** extends freely through motor **78** and the lower end of the rod **1** is provided with a sensor or shoe **82**, which is adapted to ride on the surface **2** of aircraft **83**. Sensor **82** is biased downwardly against the aircraft surface **2** by a coil spring **84**, which is interposed between the motor **78** and the upper surface of the sensor.

In the non-destructive inspection system, one or more robots **1** are mounted to travel across the surface of the aircraft **83**, as illustrated in FIG. **8**. In practice, three robots **1** can be utilized along with six laser tracking units **85** when inspecting a large commercial aircraft. As shown in FIG. **7**, a movable carriage **86** is associated with each robot and includes a vacuum pump, that is connected by a suitable conduit **87** to the manifolds **28** on the robot. In addition, electric feed lines not shown, are connected between the carriage **86** and the robot **1**. As illustrated in FIG. **7**, one of the carriages **86** is mounted to travel on an overhead track **88** and is connected to a robot **1** which is adapted to move

across the upper surfaces of the aircraft 83, while a second carriage 85 travels on the ground and is operably connected top a second robot 1 that traverses the lower surface of the aircraft.

In carrying out the non-destructive inspection, the vacuum system is initially started to create a vacuum in the vacuum cups and enable the robot to adhere to the surface of the aircraft 83. The aircraft has certain tooling locations, or depressions, located at various positions on the buoyancy line, which are used as reference points to take dimensions during the manufacture and set-up of the aircraft. These depressed reference points are generally referred to as fiducials. Through a radio controlled unit, the motors 24 on the robot 1 are then actuated to move the robot over the aircraft surface until the sensor 82 is engaged with a fiducial. Through the computer of the laser system, this is established as an origin point.

As a large aircraft generally has a number of fiducials, the robot is moved and engaged with each fiducial to obtain a series of origin points.

The desired operating program as selected in the computer, then actuates the program to operate the motors 24 to move the robot in the desired path of travel on the aircraft surface. At this time, the interior of the aircraft is under atmospheric pressure. As the robot moves across the aircraft surface the sensor 82 will ride on the surface and will move relative to the frame of the robot.

As described in the tracking system of U.S. Pat. No. 4,714,339, a laser beam is directed from tracking unit 85 to the target, which is the retro-reflector 9 mounted on housing 3, and the retro-reflector reflects a beam back to a tracking unit 85. Photosensors attached to the tracking unit provide error signals to a servo system, which controls optics at the tracking unit to provide the direction necessary to accomplish the coincidence of the beams. The separation of the incident or source beam and the reflected beam are measured and by measuring the direction of the beams relative to the tracking unit or tracking point, the target can be located in spatial coordinates and the orientation of the retro-reflector 9 can be continuously determined, thus providing a surface map of the aircraft.

After the surface mapping of the entire aircraft has been completed, the interior of the aircraft is then pressurized at about 1 atmosphere of pressure and the surface mapping operation is repeated. If any portion of the aircraft surface shows a deviation under pressurized conditions beyond a given tolerance it can indicate a potential defect in the surface, such as a crack or faulty rivet. Any potential defective area can then be manually inspected.

By using the robot 1 in conjunction with a laser tracking system, surface mapping of the aircraft can be accomplished to determine potential areas of defect without the necessity of stripping paint from the aircraft surface and without the need of a manual inspection of the entire aircraft surface. As the paint stripping, manual inspection, repainting and waxing operations are eliminated, the overall time and cost for the inspection is greatly reduced.

As a further and important advantage, the invention eliminates the need of incorporating pollution control equipment, which is necessary for normal paint stripping operations. Stripping of the paint from a large commercial aircraft, such as a Boeing 747, normally requires more than 1,000 gallons of solvent, such as methylene chloride. As the solvent is toxic, and creates a potential environmental hazard, pollution control equipment is necessary to restrict the escape of solvent vapors.

It is preferred that tracks 18, as well as frame 4, be constructed of flexible plastic material so that the robot can conform to contoured surfaces.

Various modes of carrying out the invention are contemplated as being within the scope of the following claims, particularly pointing out and distinctly claiming the subject matter which is regarded as the invention.

I claim:

1. A method for non-destructive inspection of an aircraft, comprising the steps of positioning a robot on the outer surface of an aircraft, mounting a surface sensor for movement on the robot and positioning the sensor in contact with the outer surface of the aircraft, maintaining the interior of the aircraft at a first pressure, moving the robot in a selected path of travel over said surface with said sensor riding on said surface and moving relative to said robot, tracking the movement of said sensor to provide a first continuous measurement of the spatial coordinates of said sensor, pressurizing the interior of the aircraft to a pressure greater than said first pressure, repeating the steps of moving the robot and tracking the movement of the sensor to provide a second continuous measurement of the spatial coordinates of the sensor, and comparing the first measurement with the second measurement to determine whether the spatial coordinates at any selected location on said aircraft outer surface are outside of a given tolerance.

2. The method of claim 1, wherein the step of mounting the sensor for movement comprises mounting the sensor for movement on the robot in a direction normal to the direction of travel of the robot.

3. The method of claim 1, wherein the first pressure is atmospheric pressure and the second pressure is above atmospheric pressure.

4. The method of claim 1, wherein the step of tracking the sensor comprises mounting a retro reflector on the sensor, directing an incident laser beam from a laser tracking unit toward the retro reflector, reflecting the beam from the retro reflector back toward the laser tracking unit, and comparing the incident beam with the reflected beam to provide a measurement of the spatial coordinates.

5. The method of claim 1, and including the step of biasing the sensor into contact with said outer surface.

6. A method for non-destructive inspection of an aircraft, comprising the steps of positioning a robot on a surface of an aircraft, mounting a surface sensor for movement on the robot and positioning the sensor in contact with the surface of the aircraft, maintaining the interior of the aircraft at a first pressure, moving the robot in a selected path of travel over said surface with said sensor riding on said surface and moving relative to said robot, directing an incident laser beam from a laser generating unit located a remote location relative to said robot toward a retro-reflector mounted on the sensor, reflecting the laser beam from the retro-reflector back toward the laser generating unit, comparing the incident beam with the reflected beam to provide a first measurement of spatial coordinates of the sensor, subjecting the interior of the aircraft to a second pressure different from said first pressure, repeating the steps of moving the robot and tracking the movement of the sensor to provide a second continuous measurement of the spatial coordinates of the sensor, and comparing the first measurement with the second measurement to determine whether the spatial coordinates at any selected location on said aircraft surface are outside of a given tolerance.

* * * * *

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United States Patent [19]

Bar-Cohen et al.

[11] **Patent Number: 6,105,695**

[45] **Date of Patent: Aug. 22, 2000**

[54] **MULTIFUNCTION AUTOMATED CRAWLING SYSTEM**

[75] Inventors: **Yoseph Bar-Cohen**, Seal Beach; **Benjamin Joffe**, Chatsworth; **Paul Gregory Backes**, La Cresenta, all of Calif.

[73] Assignee: **California Institute of Technology**, Pasadena, Calif.

[21] Appl. No.: **09/220,493**

[22] Filed: **Dec. 22, 1998**

Related U.S. Application Data

[62] Division of application No. 08/691,202, Aug. 1, 1996, Pat. No. 5,890,553.

[51] **Int. Cl.**[7] **B62D 57/032**

[52] **U.S. Cl.** **180/8.5**; 901/1

[58] **Field of Search** 180/8.1, 8.5, 8.6, 180/164; 901/1

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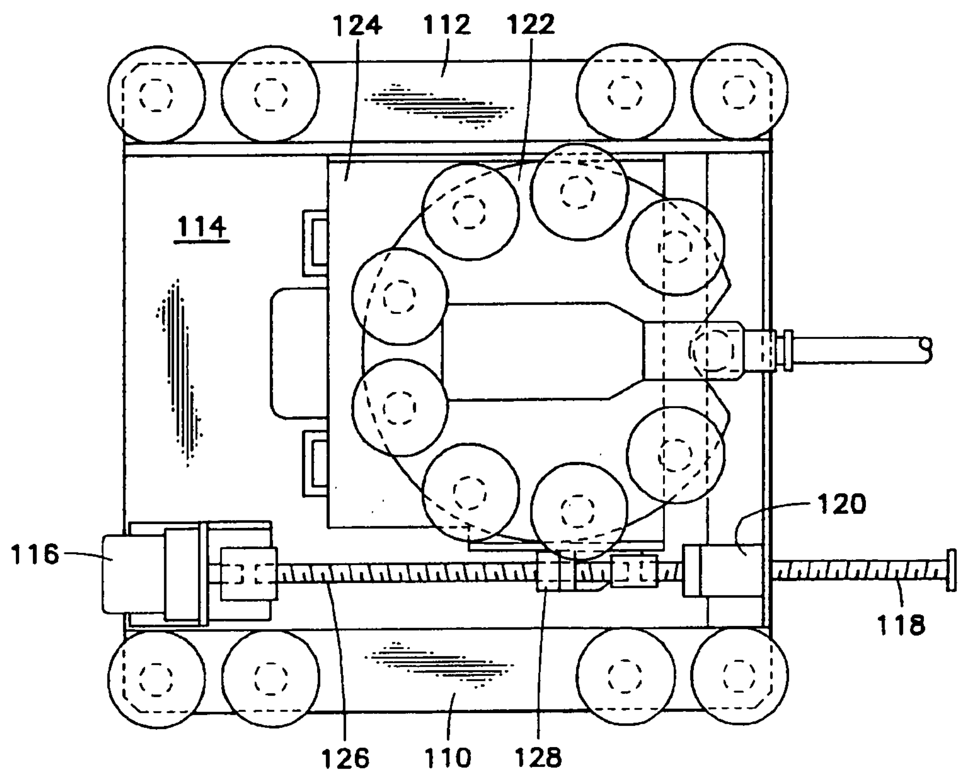
Primary Examiner—J. J. Swann
Assistant Examiner—J. Allen Shriver
Attorney, Agent, or Firm—Michaelson & Wallace

[57] **ABSTRACT**

The present invention is an automated crawling robot system including a platform, a first leg assembly, a second leg assembly, first and second rails attached to the platform, and an onboard electronic computer controller. The first leg assembly has an intermittent coupling device and the second leg assembly has an intermittent coupling device for intermittently coupling the respective first and second leg assemblies to a particular object. The first and second leg assemblies are slidably coupled to the rail assembly and are slidably driven by motors to thereby allow linear movement. In addition, the first leg assembly is rotary driven by a rotary motor to thereby provide rotary motion relative to the platform. To effectuate motion, the intermittent coupling devices of the first and second leg assemblies alternately couple the respective first and second leg assemblies to an object. This motion is done while simultaneously moving one of the leg assemblies linearly in the desired direction and preparing the next step. This arrangement allows the crawler of the present invention to traverse an object in a range of motion covering 360 degrees.

11 Claims, 8 Drawing Sheets



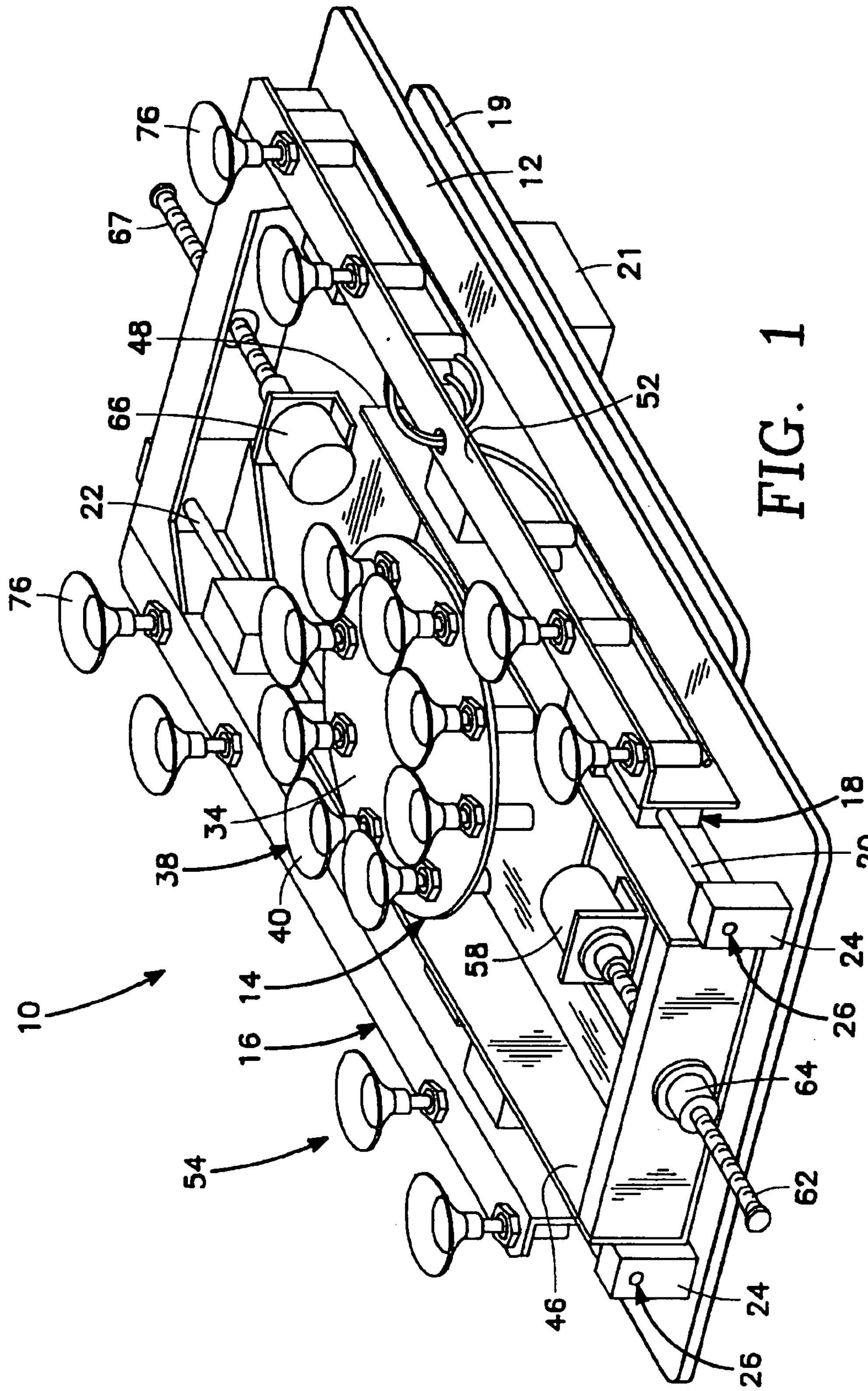

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FIG. 1

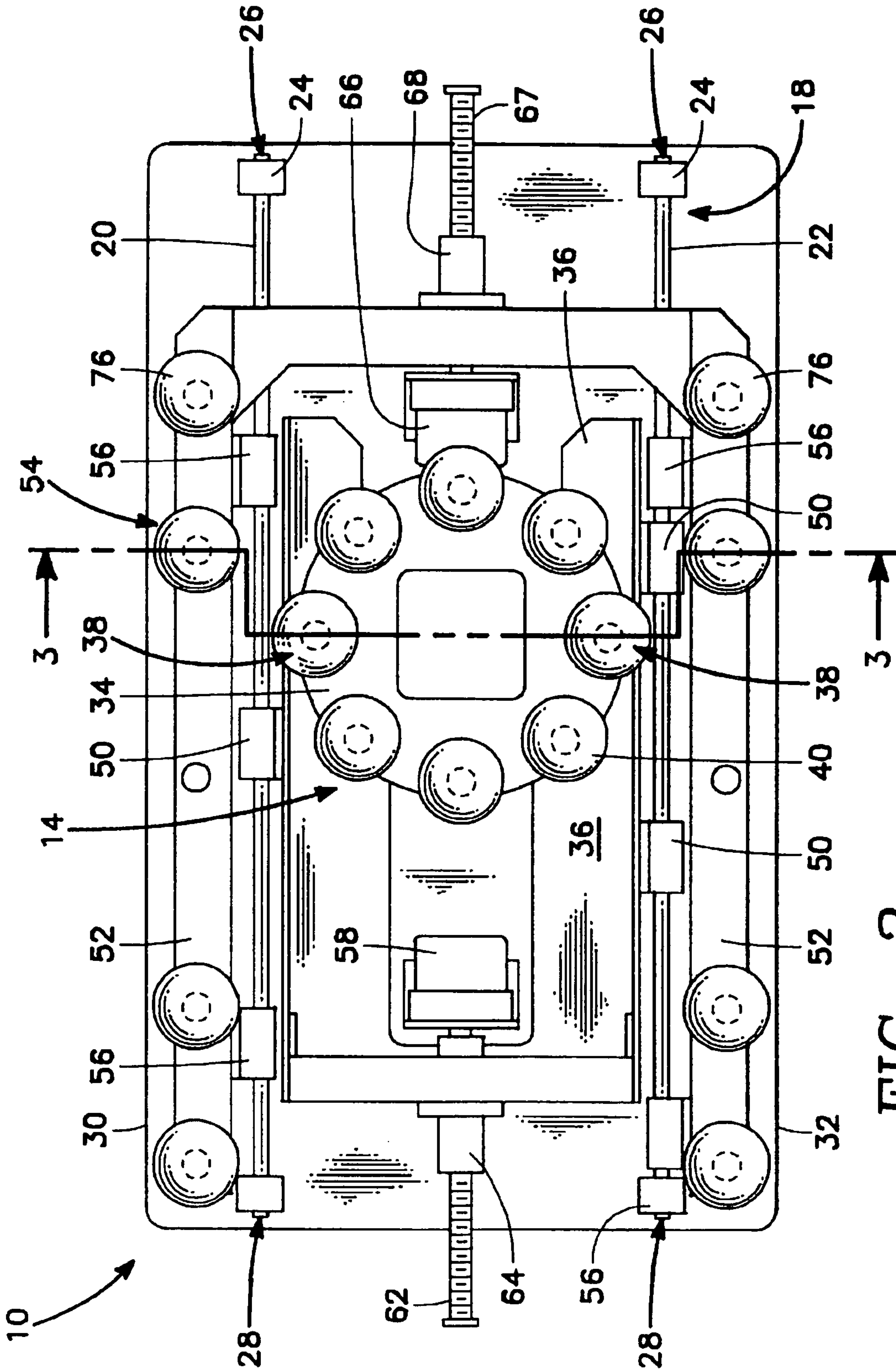
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FIG. 2

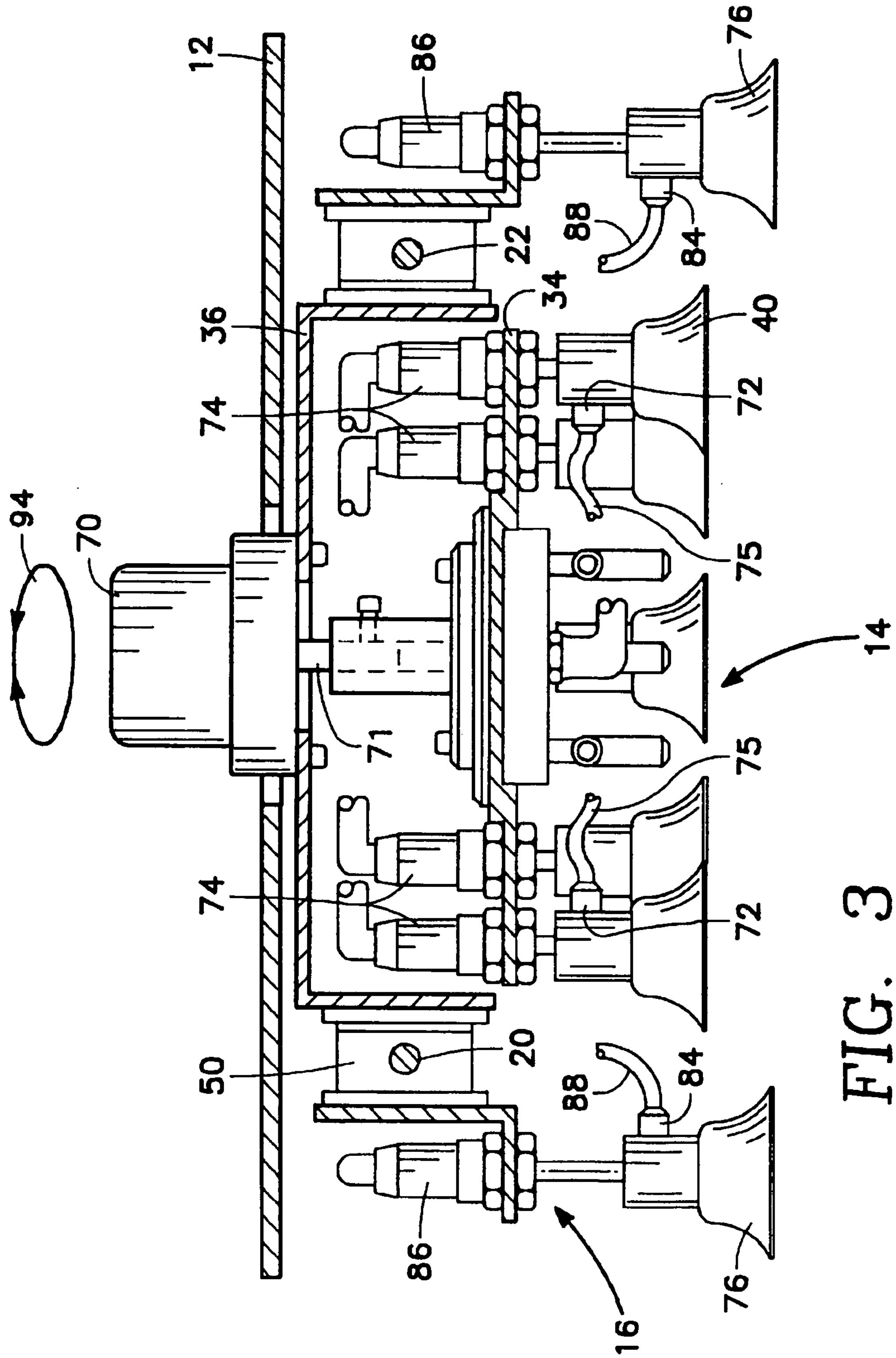

FIG. 3

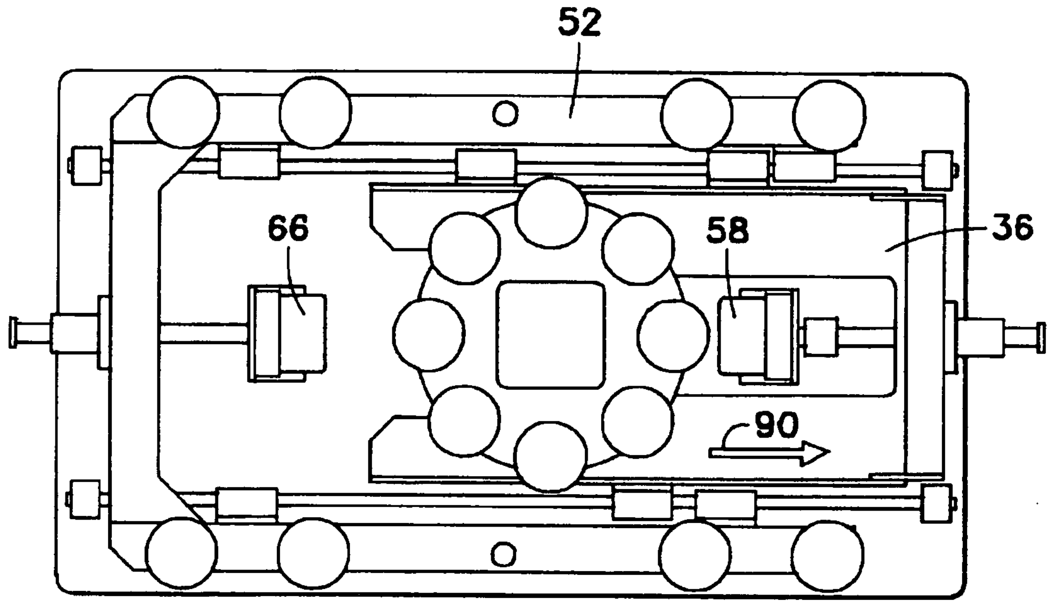

FIG. 4

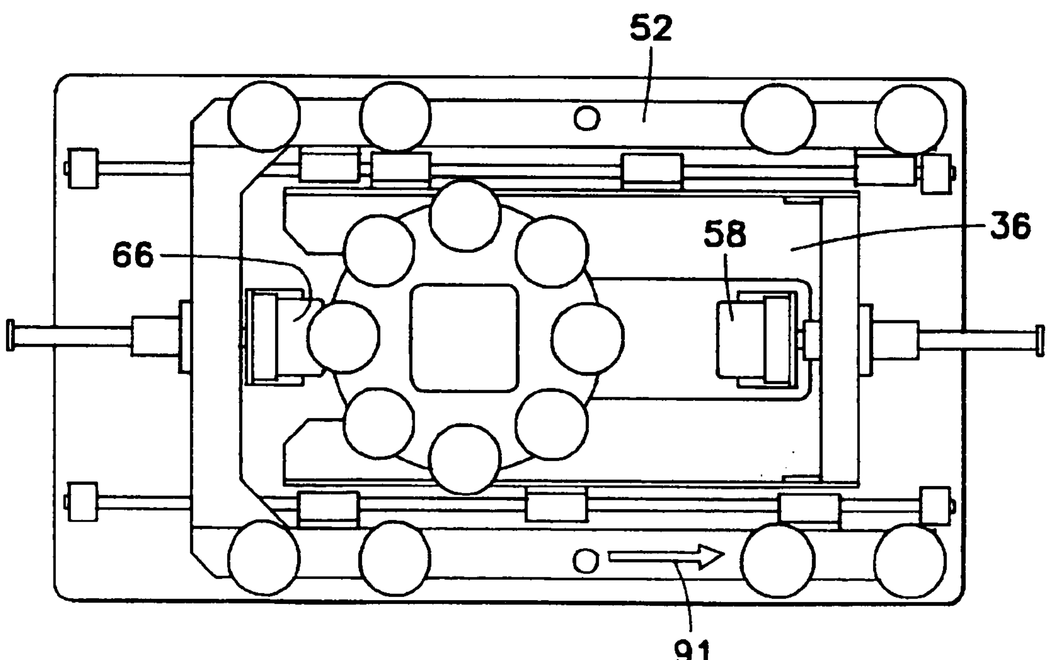

FIG. 5

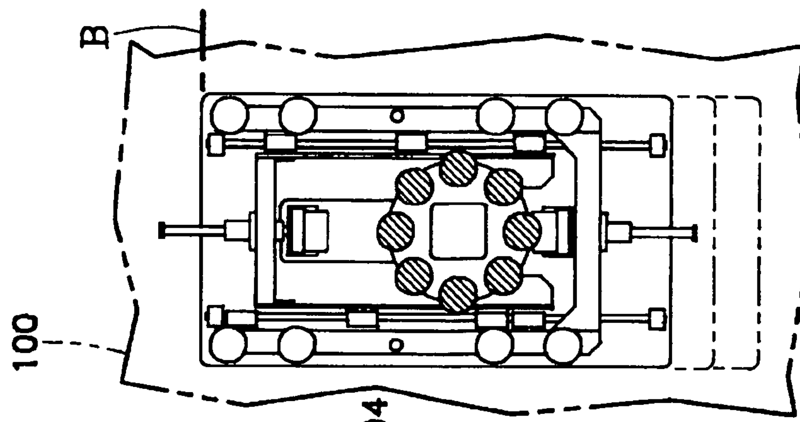

FIG. 9

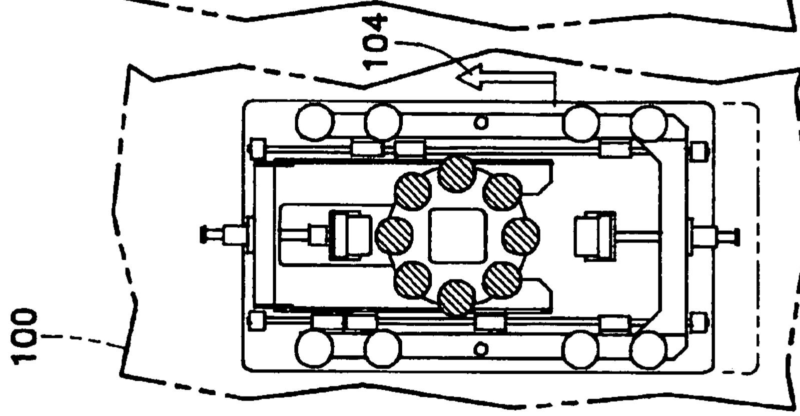

FIG. 8

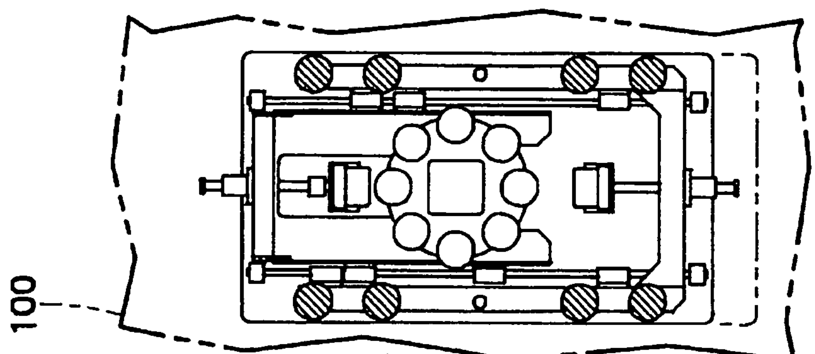

FIG. 7

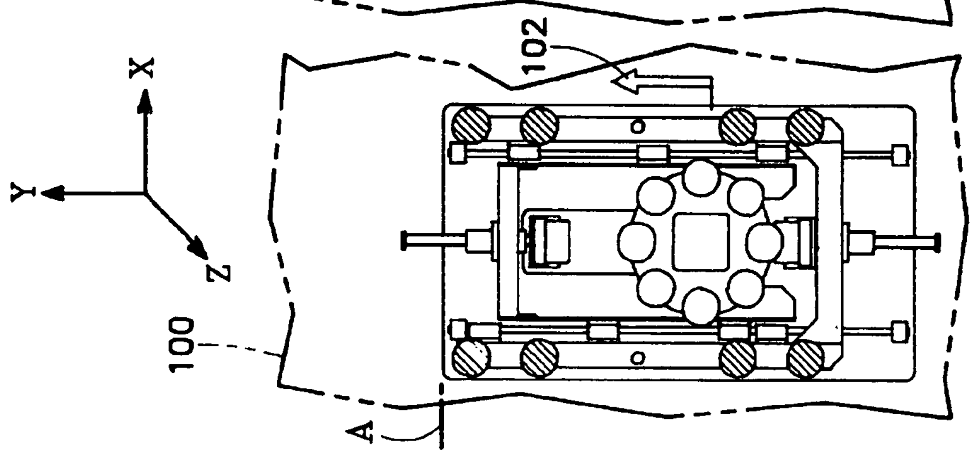

FIG. 6

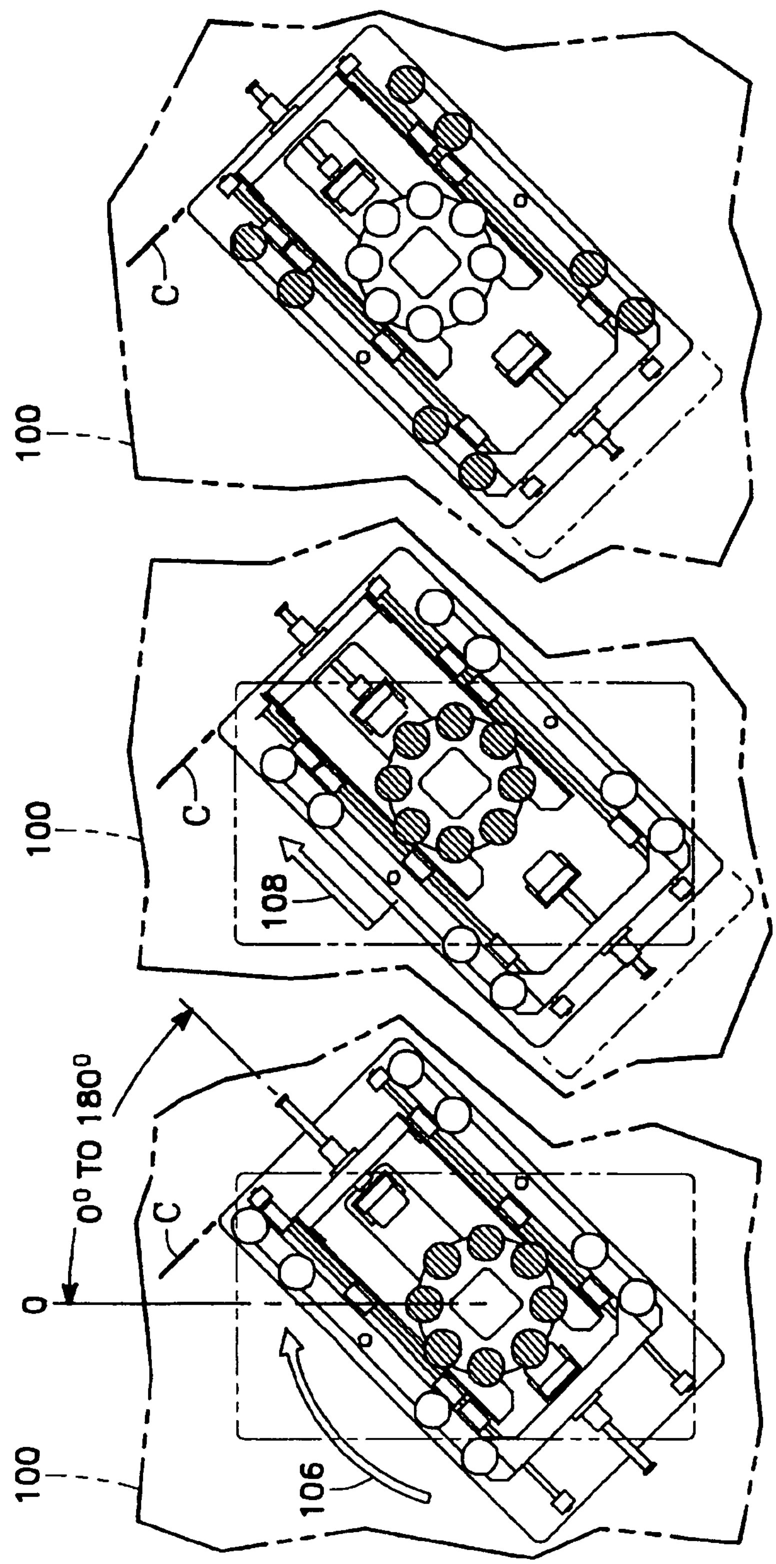

FIG. 10

FIG. 11

FIG. 12

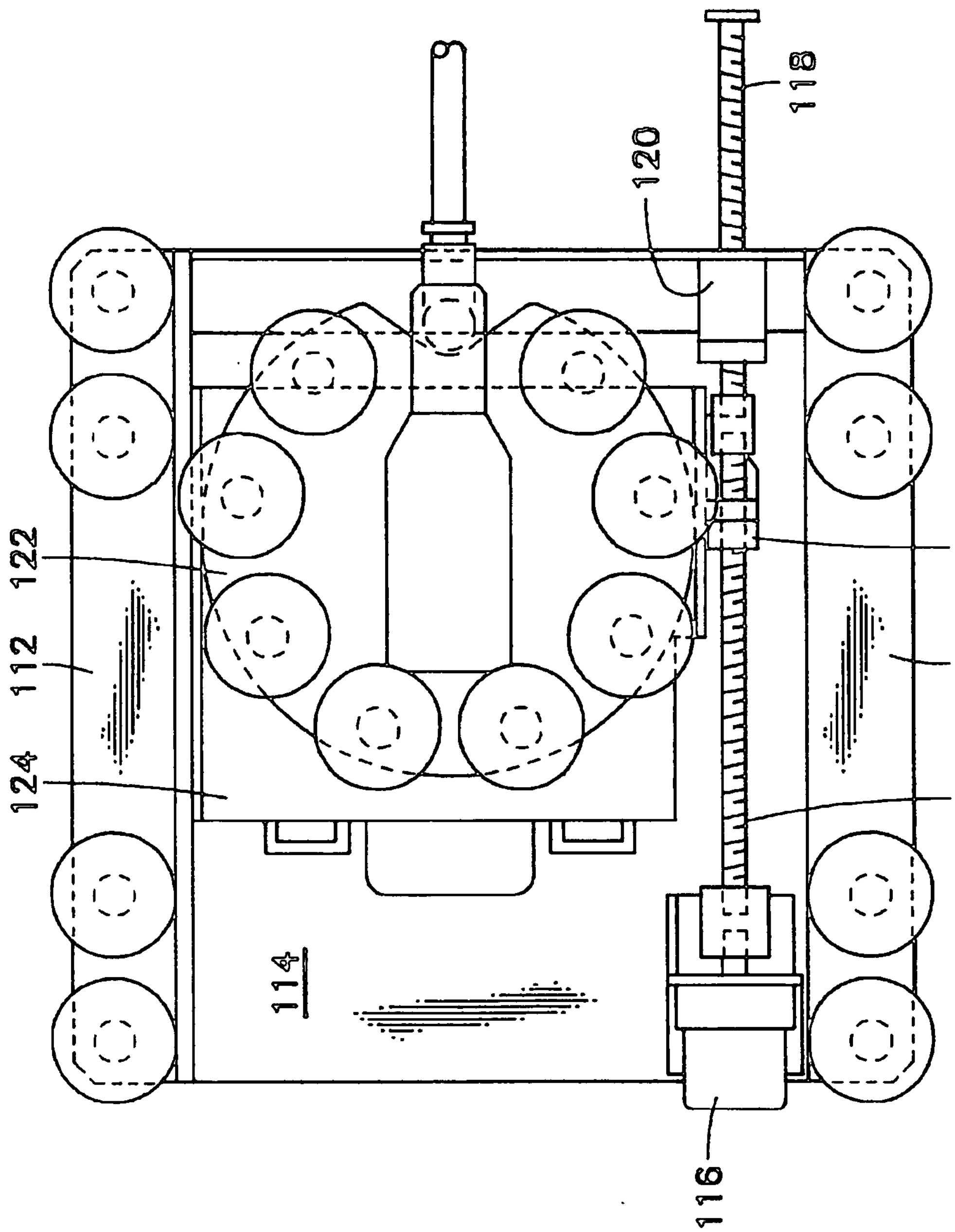

FIG. 13

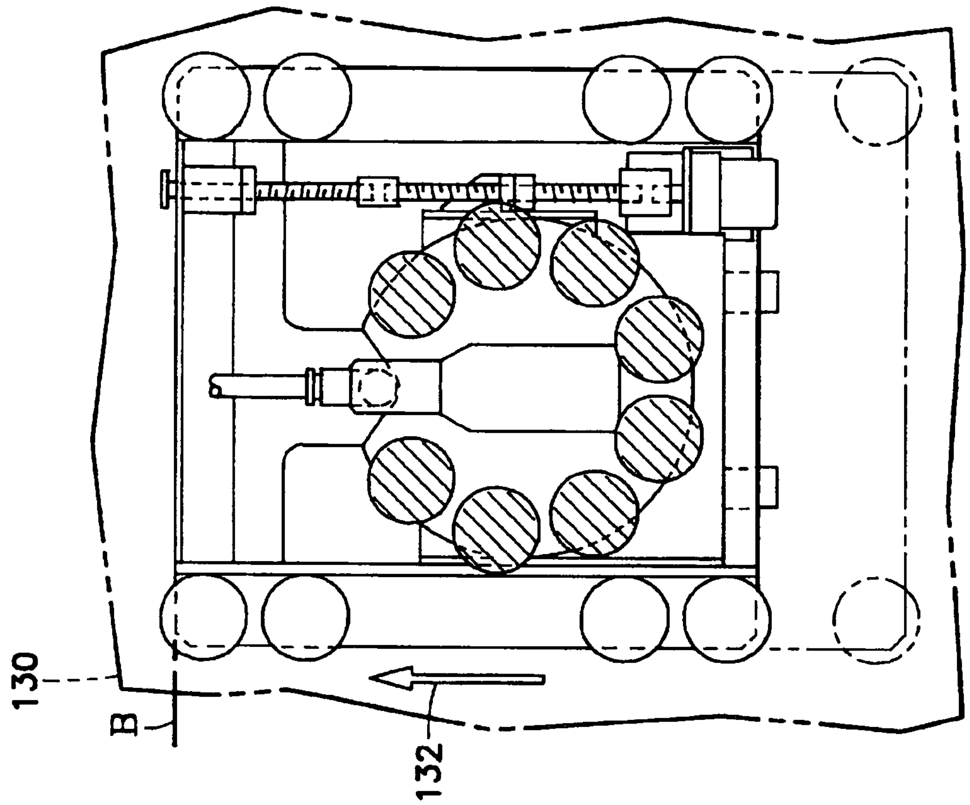

FIG. 15

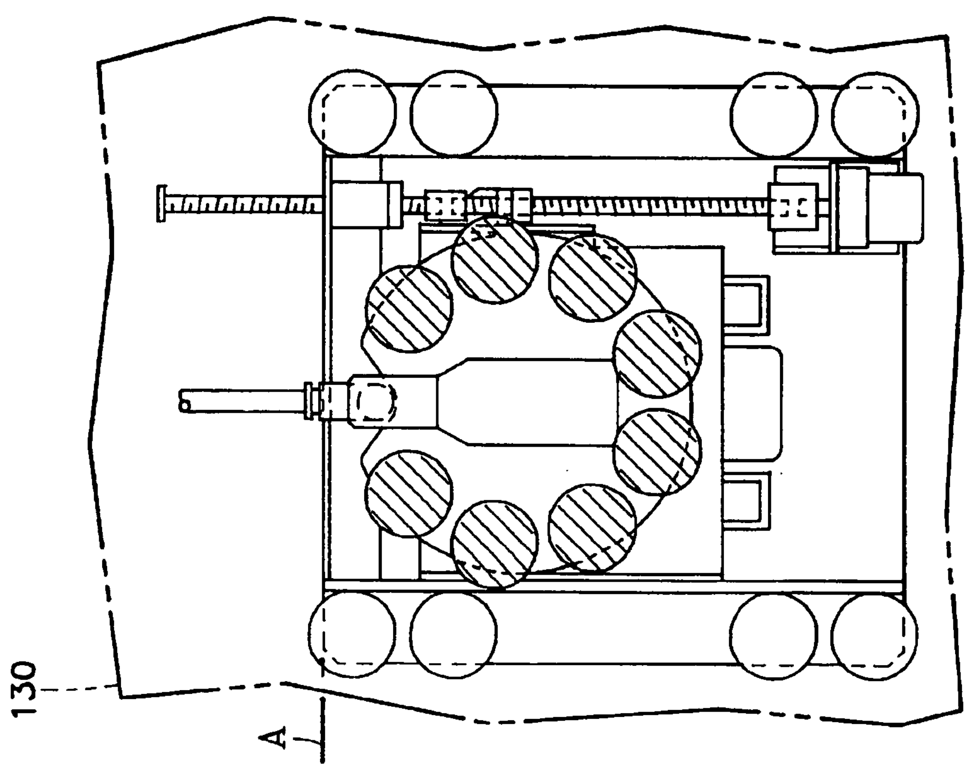

FIG. 14

MULTIFUNCTION AUTOMATED CRAWLING SYSTEM

This is a divisional of application Ser. No. 08/691,202, filed Aug. 1, 1996 Ser. No. 5,890,553.

BACKGROUND OF THE INVENTION

1. Origin of the Invention

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the contractor has elected to retain title.

2. Field of the Invention

The present invention relates to automated robot systems, and in particular to an automated crawling robot with multifunctional purposes, such as performing labor intensive tasks and/or dangerous field tasks.

3. Related Art

Automated robotic crawling systems are needed to perform labor intensive and dangerous field tasks in the areas of structures inspection/repair. Typical tasks for crawling systems include inspection of repairs of aircraft, detection of cracks, dents, corrosion, impact damage, delaminations, fire damage, porosity, and other flaws in structures. Also, crawling systems are needed for the performance of specific tasks, such as hazardous material handling, including toxic materials and bombs.

Current crawling systems include, for instance, a tank crawler and a cruciform crawler. The tank crawler has a body with a continuous belt having a vacuum pad with numerous suckers. Each sucker is connected to an air duct inside the continuous belt and has a mechanical valve. For each sucker, the valve opens mechanically when the sucker touches the surface of a particular object to thereby allow the sucker to cling to the surface. A motor, timing belt, and timing pulley are located within the body and operate to turn the continuous belt to provide the tank crawler with secure movement over a surface of an object.

The cruciform crawler comprises a horizontal spine and vertical bridges. Both the horizontal spine and the bridges have plural suction cups for secure coupling to a particular object. In order to effectuate movement of the cruciform crawler, the vertical bridges are moved forward while the suction cups of the horizontal spine are secured to an object. Next, the spine is moved forward while the suction cups of the vertical bridges are secured to complete one cycle. Each cycle produces linear movement of the cruciform crawler across an object.

Although the tank crawler has proven useful for certain tasks, the tank crawler is cumbersome, is large and bulky, and has limited movement. For example, the tank crawler cannot perform difficult maneuvers and does not provide a full range of motion. Thus, the limited motion of the tank crawler, as well as the cumbersome, bulky, and large size of the tank crawler, prohibits it from performing certain important tasks. In addition, steering the tank causes wear to the suckers which are attached to the belt.

With regard to the cruciform crawler, the movement of the cruciform crawler is limited to mainly linear movement and not sharp angular maneuvers. Consequently, does not allow a full 360 degree range of motion over a point. Thus, the limited motion of the cruciform crawler prohibits it from performing certain important tasks. In addition, similar to the suckers of the tank crawler, the suckers are subject to wear during maneuver.

Many current crawling systems are heavy, are complex to operate and maneuver, have high power requirements involved with preparation time between steps and have low payload/crawler weight ratio. Moreover, since these current crawling systems are designed for specific tasks, they have limited uses and cannot be utilized for a variety of tasks. Further, existing crawling systems do not have carrying areas for carrying observation cameras, sensors and sensor manipulation devices, and data gathering equipment such as computer processors, for transporting hazardous materials, for retrieving items and objects, etc.

Therefore, what is needed is a portable, user friendly automated robotic crawling system that can move rapidly over large areas with a full range of motion, perform a wide variety of tasks in all types of environments, including hostile environments, and access difficult to reach areas. What is further needed is a crawling system that has a carrying area for carrying observation cameras, sensors and sensor manipulation devices, and data gathering equipment such as computer processors, for transporting hazardous materials, and for retrieving items and objects.

Whatever the merits of the above mentioned systems and methods, they do not achieve the benefits of the present invention.

SUMMARY OF THE INVENTION

To overcome the limitations in the prior art described above, and to overcome other limitations that will become apparent upon reading and understanding the present specification, the present invention is an automated crawling robot system with multifunctional purposes.

The automated crawling system includes a platform, a first leg assembly, a second leg assembly, first and second guiding rails attached to the platform, and an onboard electronic computer controller. The onboard computer can control the movement of the robot and can have preprogrammed instructions or can accept remote commands. The first and second leg assemblies have intermittent coupling devices for intermittently coupling the respective first and second leg assemblies to a particular object.

The first leg assembly is slidably coupled to the first rail and is slidably driven by a first motor to thereby effectuate linear movement of the first leg assembly relative to the platform. Similarly, the second leg assembly is slidably coupled to the second rail and is slidably driven by a second motor to thereby effectuate linear movement of the second leg assembly relative to the platform. In addition, the first leg assembly is rotatably coupled to the platform and is rotary driven by a rotary motor to thereby provide rotary motion to the first leg assembly relative to the platform.

The intermittent coupling devices of the first and second leg assemblies alternately couple the respective first and second leg assemblies to an object. Specifically, the crawler of the present invention effectuates movement with repetitive cyclic actions. For each cycle, first the intermittent coupling device of the first leg assembly is initially coupled to a particular object while the intermittent coupling device of the second leg assembly remains uncoupled to the object. Next, the second assembly is linearly traversed by the second motor.

Also, it should be noted that the first leg assembly can be linearly traversed by the first motor or rotatably traversed by the rotary motor either separately or simultaneously. This arrangement allows the crawler of the present invention to traverse an object in a range of motion covering 360 degrees.

Another feature of the present invention is the carrying area for carrying observation cameras, sensors and sensor

manipulation devices, and data gathering equipment such as computer processors, for transporting hazardous materials, and for retrieving items and objects. Another feature of the present invention is its intermittent coupling devices which allow the automated crawling system to traverse an object rapidly. Yet another feature is simultaneous preparation of a subsequent step while a previous step is being completed.

An advantage of the automated crawling system of the present invention is the ability to perform multifunctional operations. Another advantage of the automated crawling system of the present invention is that it is portable, can obtain rapid movements over large areas, and can perform a wide variety of tasks in all types of environments, including hostile environments and environments with difficult to reach areas. Yet another advantage of the present invention is that it has low power requirements and has a high payload/crawler weight ratio. Yet another advantage is speedy traversal due to efficient time management.

The foregoing and still further features and advantages of the present invention as well as a more complete understanding thereof will be made apparent from a study of the following detailed description of the invention in connection with the accompanying drawings and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

FIG. 1 is a perspective view of the automated crawling system of the present invention;

FIG. 2 is a bottom view of the automated crawling system of the present invention;

FIG. 3 is a cross sectional side view of the automated crawling system of the present invention;

FIG. 4 is a bottom view of the first leg of the automated crawling system at its front-most extreme position and the second leg at its rear-most extreme position;

FIG. 5 is a bottom view of the first leg of the automated crawling system at its rear-most extreme position and the second leg at its front-most extreme position;

FIGS. 6–12 illustrate sequential movement of the automated crawling system from point A to point B;

FIG. 13 is an alternative embodiment of the present invention; and

FIGS. 14–15 illustrate sequential movement of the automated crawling system of FIG. 13.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

FIG. 1 is a perspective view of the automated crawling system of the present invention. FIG. 2 is a bottom view of the automated crawling system of the present invention.

Structural Components

The present invention is an automated crawling system **10** including a platform **12**, such as a flat platform, a first leg assembly **14**, a second leg assembly **16**, a rail assembly **18**, and an onboard electronic computer controller **21**. The carrying area **19** can carry observation cameras, sensors and sensor manipulation devices, and data gathering equipment such as computer processors, and can transport hazardous materials, and can retrieve items and objects. The onboard computer controller **21** can control the movement of the robot with preprogrammed instructions or can accept remote commands.

The rail assembly **18** comprises a first rail **20**, a second rail **22**, and rail supports **24** located at an end **26**, **28** of each rail **20**, **22**, respectively. The first and second rails **20**, **22** are attached or mounted to the platform **12** and extend along opposite longsides **30**, **32** of the platform **12** of the crawler **10**.

The first leg assembly **14** comprises a mounting disc **34**, such as a circular flat disc, a first bracket **36**, and an intermittent coupling device **38**, such as a plurality of vacuum cups **40**. The intermittent coupling device **38** can comprise any mechanism suitable for intermittent coupling to a particular object (described in detail in the Operation section below). For example, an intermittent coupling device with a vacuum cup arrangement **40**, as shown in FIG. 1, is suitable for intermittent coupling to a surface of a particular object and will be described hereafter as a working example. However, for ferromagnetic objects or objects with ferromagnetic surfaces, a magnetic device having intermittent activated solenoids can be utilized as the intermittent coupling device.

The mounting disc **34** is attached to the first bracket **36**. The first bracket **36** preferably has two strips **46**, **48** extending outwardly from the platform **12**. A plurality of sliders **50** are preferably attached to each outside portion of the strips **46**, **48** of the first bracket **36**. Each slider **50** is also slidably coupled to one of the rails **20**, **22** of the rail assembly **18**. The sliders **50** provide the first bracket **36** with freedom of linear movement relative to the platform **12**.

The second leg assembly **16** comprises a second bracket **52** and an intermittent coupling device **54** similar to the intermittent coupling device **38** of FIG. 1, which is preferably a plurality of vacuum cups **76** (similar to vacuum cups **40** of FIG. 2). The second bracket **52** is preferably a "U" shaped bracket with a topside surface and opposite inside surfaces. The second bracket **52** has a plurality of sliders **56** (similar to sliders **50** of FIG. 2) preferably attached to each inside surface of the second bracket **52**. Each slider **56** is also slidably coupled to one of the rails **20**, **22** of the rail assembly **18**.

A first motor **58**, which can be a conventional electric motor, is rigidly attached to the platform **12**. The first motor **58** has a ball screw shaft **62** coupled to a first receiver **64** which can be attached to or integral with the first bracket **36**. Also, the first motor **58** can have encoders (not shown) to determine the position of traversal of the first bracket **36**. Since the first bracket **36** is slidably coupled to the platform **12** and the first receiver **64** is rigidly attached the first bracket **36**, the first motor **58** and the ball screw shaft **62** provide the first bracket **36** with linear motion, relative to the platform **12**, in either a forward or reverse direction (described in detail in the Operation section below).

Similar to the first motor **58** configuration, a second motor **66** is rigidly attached to the platform **12**. The second motor **66** has a ball screw shaft **67** coupled to a second receiver **68** which can be attached to or integral with the second bracket **52**. Also, the second motor **66** can have encoders (not shown) to determine the position of traversal of the second bracket **52**. Since the second bracket **52** is slidably coupled to the platform **12** and the second receiver **68** is rigidly attached the second bracket **52**, the second motor **66** and the

ball screw shaft 67 provide the second bracket 52 with linear motion, relative to the platform 12, in either a forward or reverse direction (described in detail in the Operation section below).

FIG. 3 is a cross sectional side view of the automated crawling system of the present invention of FIG. 2. A rotary motor 70, which can be an ultrasonic motor, such as a low mass compact ultrasonic motor, or other type of rotary motor, is preferably attached to the first bracket 36 and is coupled to the mounting disc 34 via a shaft 71. The rotary motor 70 provides the mounting disc 34 with rotary motion in either a clockwise or counter clockwise direction.

Referring to FIG. 3 along with FIGS. 1 and 2, the vacuum cups 40 of the first leg assembly 14 are preferably attached to the mounting disc 34 so that they protrude from the mounting disc 34 as shown in FIG. 3. Each vacuum cup 40 has a separate vacuum pump 72 and a separate air cylinder 74 coupled to it and attached to the mounting disc 34. Each vacuum pump 72 provides such vacuum cup with a vacuum source independent of the other vacuum cups; such as a venturi vacuum pump.

The vacuum pumps 72 and the air cylinders 74 are also coupled to a standard air compressor (not shown) for providing each vacuum pump 72 and air cylinder 74 with air pressures preferably ranging from 70–120 psi. Flexible tubing 75, such as polyethylene tubing, PVC tubing, or the like, provides a means for transferring the air pressure from the air compressor to each vacuum pump 72 and each air cylinder 74.

The vacuum cups 76 of the second leg assembly 16 are preferably attached to the second bracket 52 so that they protrude from the topside surface of the second bracket 54. Similar to the vacuum cups 40 of the first leg assembly 14, each vacuum cup 76 of the second leg assembly 16 has a separate vacuum pump 84 coupled to it and attached to the second bracket 52. Also, each vacuum cup 76 of the second leg assembly 16 has a separate air cylinder 86 coupled to it and mounted behind each vacuum cup 76.

In addition, similar to the vacuum pumps 72 of the first leg assembly 14, each vacuum pump 84 of the second assembly 16 is preferably a venturi vacuum pump. Moreover, the air cylinders 86 and the vacuum pumps 84 of the second assembly 16 are coupled to the same air compressor (not shown) as the vacuum pumps 52 and air cylinders 54 of the first leg assembly 14. Flexible tubing 88 similar to flexible tubing 75 is used with the second leg assembly 16. As stated above, it should be noted that the intermittent coupling devices 38, 54 can be any device suitable for coupling to an object is not limited to being a vacuum pump device.

FIG. 4 is a bottom view of the first leg assembly and the second leg assembly of the automated crawling system of the present invention at their front-most extreme positions, respectively. FIG. 5 is a bottom view of the first leg assembly and the second leg assembly of the automated crawling system of the present invention at their rear-most extreme positions, respectively.

In addition, the rotary motor 70 allows movement of the first leg assembly 14 rotationally along the shaft 71, in the direction indicated by arrow 94 as shown in FIG. 3. A detailed description of the operation and the interaction of the components of the crawler 10 will be discussed in the Operation section below.

Operation

FIGS. 6–12 illustrate sequential movement of the automated crawling system from point A to point B to point C along x and y axes and around a z axis. The onboard computer controller 21 can control the movement of the robot with preprogrammed instructions or can accept remote commands. The crawler of the present invention effectuates movement with repetitive cyclic actions.

FIGS. 6–9 illustrate one cycle of linear movement and FIGS. 10–12 illustrate rotational movement. For each cycle, first referring to FIG. 6, the intermittent coupling device 54 of the second leg assembly 16 is initially coupled (as indicated by shading of the intermittent coupling device 54 of FIG. 6) to a particular object 100. During this, the intermittent coupling device 38 of the first leg assembly 14 remains uncoupled (as indicated by non-shading of the intermittent coupling device 38 of FIG. 6) to the object 100.

Next, as shown in FIG. 7, the second leg assembly 16 is linearly traversed by the second motor 66. Linear movement of the platform 12 relative to the object 100, as indicated by arrow 102, is accomplished by operating the second motor 66. As the second motor 66 operates, the ball screw shaft 67 traverses along the second receiver 68. After traversal, the second leg assembly 16 is uncoupled from the object 100.

Third, as shown in FIG. 8, the intermittent coupling device 38 of the first leg assembly 14 is coupled (as indicated by shading of the intermittent coupling device 38 of FIG. 7) to the object 100 while the intermittent coupling device 54 of the second leg assembly 16 remains uncoupled (as indicated by non-shading of the intermittent coupling device 54 of FIG. 7) to the object 100. It should be noted that while the previous step is being completed, the crawler 10 prepares a subsequent step for movement by operating the first motor 58. One of the leg assemblies 14 or 16, move relative to the object 100.

Fourth, as shown in FIG. 9 and similar to the movement of the second leg assembly 16, linear movement of the platform 12 relative to the object 100, as indicated by arrow 104, is accomplished by operating the first motor 58. As the first motor 58 operates, the ball screw shaft 62 traverses along the first receiver 64. Since the first receiver 64 is rigidly attached to the second bracket 52, the first motor 58 is rigidly attached to the platform 12, and the platform 12 is slidably attached to the second bracket 52 via the rails 20, 22, linear movement (forward or reverse) of the second bracket 52 along the rails 20, 22 relative to the platform 12 is accomplished.

Further, as shown in FIG. 10, the crawler of the present invention can rotationally change direction of movement with a 360 degree range of motion. For example, first the intermittent coupling device 38 of the first leg assembly 14 is coupled (indicated by shading of the intermittent coupling device 38 of FIG. 10) to the object 100. Next, the intermittent coupling device 54 of the second leg assembly 16 is uncoupled (indicated by non-shading of the intermittent coupling device 54 of FIG. 7) to the object 100.

The rotary motor 70 is then operated for providing the mounting disc 34 with rotary motion in either a clockwise, as indicated by arrow 106 to reach point C, or counter clockwise direction. Since the rotary motor 70 provides relative rotational motion between the mounting disc 34 and the first bracket 36, and the first bracket 36 is attached to the platform 12, the platform 12 rotates during operation of the rotary motor 70, with a range of motion of 360 degrees.

After the desired rotation of the crawler is achieved, the crawler can be linearly traversed by repeating cycles of movement as discussed above. As shown in FIG. 11, the intermittent coupling device 54 of the second leg assembly 16 is again coupled (as indicated by shading of the intermittent coupling device 54 of FIG. 11) to the object 100.

During this, the intermittent coupling device **38** of the first leg assembly **14** is uncoupled (as indicated by non-shading of the intermittent coupling device **38** of FIG. **11**) to the object **100**. Next, as shown in FIG. **12**, the second leg assembly **16** is linearly traversed, as indicated by arrow **108**, by the second motor **66** in accordance with the above discussion.

FIG. **13** is an alternative embodiment of the present invention. Alternatively, a more compact crawler is disclosed with a second leg assembly **110** having a compact bracket **112** slidably coupled to a platform **114**. The crawler also includes a motor **116**. The second leg assembly has a second ball screw **118** and a second receiver **120** operated by the motor **116** and physically located on one side of the platform **114**. The crawler further includes a first leg assembly **122** having a compact bracket **124** slidably coupled to the platform **114** and a first ball screw **126** and a first receiver **128** operated by the motor **116** and physically located opposite the second ball screw **118**. The first ball screw **126** of the first leg assembly **122** has an opposite pitch from the second ball screw **118** (i.e., right versus left hand threads) and is attached to the second ball screw **118** so that the motor **116** drives both ball screws **118**, **126**.

Linear movement of the platform **114** of FIG. **13** via the leg assemblies **110**, **124** is similar to the linear movement of the platform **12** of FIGS. **6–12** with the exception of using only one motor for linear motion. Specifically, the one motor **116** turns both the first ball screw **126** and the second ball screw **118**. Thus, the crawler is more compact and has fewer motors.

For instance, as shown in FIG. **14**, the first leg assembly **14** is coupled (as indicated by shading of the first leg assembly **122** of FIG. **14**) to an object **130** while the second leg assembly **110** remains uncoupled (as indicated by non-shading of the second leg assembly **110** of FIG. **14**) to the object **130**. Next, as shown in FIG. **15**, linear movement of the crawler as indicated by arrow **132**, is accomplished by operating the motor **116**.

The foregoing description of the preferred embodiment of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

What is claimed is:

1. An automated crawling robot system for traversing about an object with a range of motion of 360 degrees, comprising:

a platform;

a first leg assembly slidably coupled to the platform and rotatably coupled to the platform and having an intermittent coupling device for intermittently coupling the first leg assembly to the object and a first ball screw and receiver system;

a second leg assembly slidably coupled to the platform and having an intermittent coupling device for intermittently coupling the second leg assembly to the object and a second ball screw and receiver system;

a motor for driving the first and second ball screw and receiver systems;

wherein said first ball screw is located opposite the second ball screw, has an opposite pitch from the second ball screw, and is attached to the second ball screw so that the motor can drive both ball screws; and

a rotary motor for rotatably traversing the second leg assembly relative to the platform.

2. The invention as set forth in claim **1**, further comprising an onboard computer controller for controlling the movement of the robot with preprogrammed instructions and with remote commands.

3. The invention as set forth in claim **1**, further comprising a carrying area for carrying data gathering equipment and for transporting materials.

4. The invention as set forth in claim **1**, wherein said platform further comprises a rail system, wherein said first and second leg assemblies slidably traverse about said rail system.

5. The invention as set forth in claim **1**, wherein said rotary motor is a low mass compact ultrasonic motor.

6. The invention as set forth in claim **1**, wherein said intermittent coupling device is a magnetic device having intermittently activated solenoids.

7. The invention as set forth in claim **1**, wherein said intermittent coupling device is a plurality of suction cups.

8. The invention as set forth in claim **7**, wherein said plurality of suction cups are a plurality of vacuum cups, each having a separate vacuum pump and a separate air cylinder coupled to it, wherein each vacuum pump provides each vacuum cup with a vacuum source independent of the other vacuum cups.

9. The invention as set forth in claim **8**, wherein said vacuum pumps are venturi vacuum pumps.

10. The invention as set forth in claim **8**, wherein said vacuum pumps and said air cylinders are coupled to a standard air compressor for providing each vacuum pump and each air cylinder with air pressures.

11. The invention as set forth in claim **10**, further comprising flexible tubing for providing a means for transferring the air pressure from the air compressor to each vacuum pump and each air cylinder.

* * * * *

US006220099B1

(12) **United States Patent**
Marti et al.

(10) **Patent No.:** **US 6,220,099 B1**
(45) **Date of Patent:** **Apr. 24, 2001**

(54) **APPARATUS AND METHOD FOR PERFORMING NON-DESTRUCTIVE INSPECTIONS OF LARGE AREA AIRCRAFT STRUCTURES**

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(73) Assignee: **CE Nuclear Power LLC**, Windsor, CT (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/231,668**

(22) Filed: **Jan. 15, 1999**

Related U.S. Application Data

(60) Provisional application No. 60/074,876, filed on Feb. 17, 1998.

(51) **Int. Cl.**^{7} **G01N 29/04**
(52) **U.S. Cl.** **73/633**
(58) **Field of Search** 73/618, 619, 620, 73/621, 622, 627, 629, 633, 634

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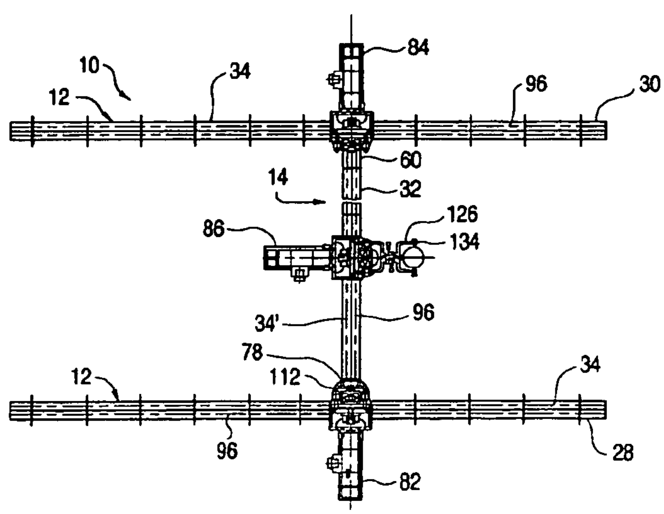
Primary Examiner—Helen Kwok
(74) *Attorney, Agent, or Firm*—Rader, Fishman & Grauer

(57) **ABSTRACT**

A surface scanner for conducting non-destructive inspection of complex surface structures and configurations. The scanner includes two flexible tracks, each fitted with a motor driven tractor assembly. A rigid beam track spans the two flexible tracks. The rigid beam track is coupled to each flexible track tractor assembly by articulating joints that permit movement at the joints along at least three independent axes. The rigid beam supports a third motorized tractor. This third tractor supports a compliant thruster assembly that deploys gimbaled mechanical impedance, ultrasonic and eddy current inspection probes. The movement of the scanner is controlled by a scan control system that includes both hardware and software for controlling the movement of the scanner over the surface to be inspected. The software also includes a teach mode that permits an operator to preprogram the scan pattern for the surface to be inspected using a global coordinate system, referencing points on the surface and the data display using an identical coordinate system. The scanner also includes a data acquisition and analysis system that control scanner functions and operations.

98 Claims, 10 Drawing Sheets



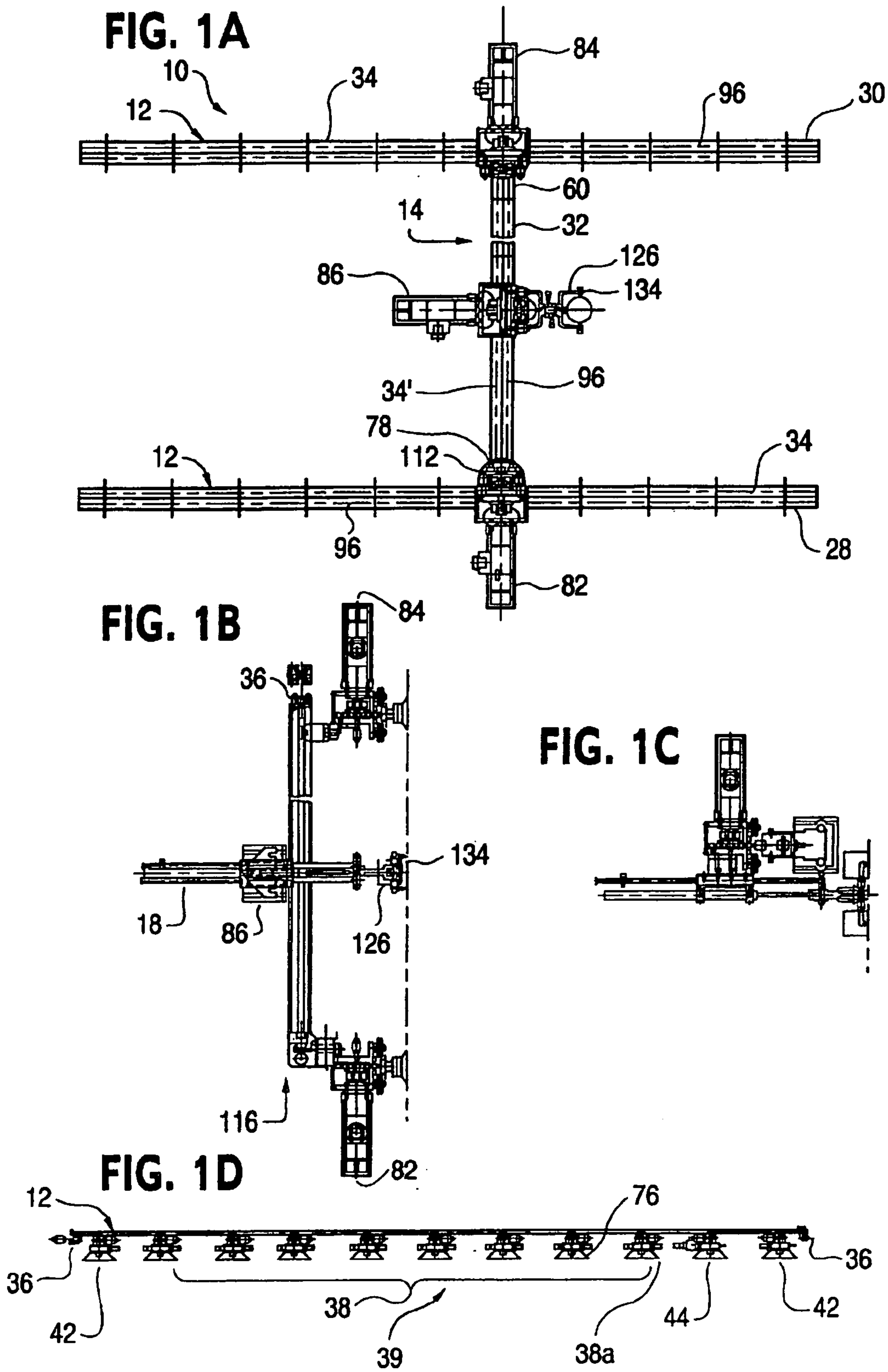


FIG. 1A
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84
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30
60
14
32
86
126
134
34'
96
78
112
12
34
96
28
82
FIG. 1B
84
36
134
18
86
126
116
82
FIG. 1C
FIG. 1D
12
76
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42
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39
38a
44
42

FIG. 2A

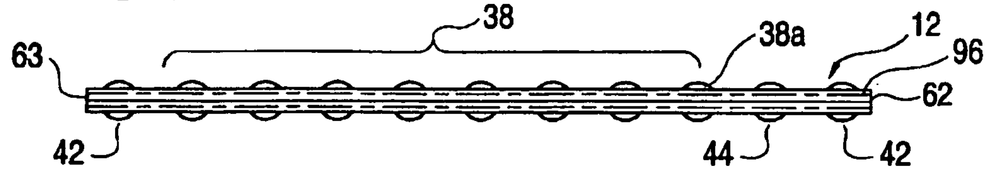


FIG. 2B

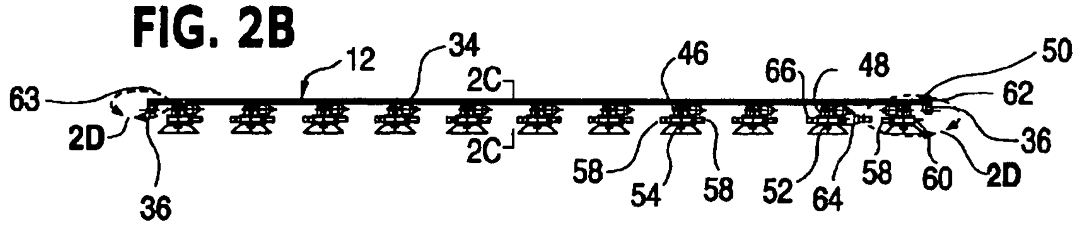


FIG. 2C

FIG. 2D

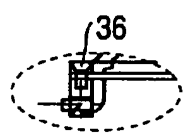


FIG. 2E

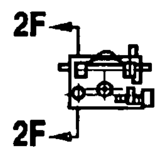


FIG. 2F

FIG. 2D'

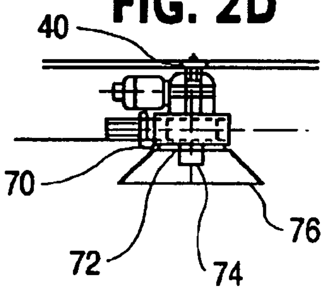


FIG. 2G

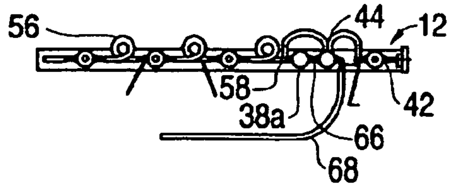


FIG. 2H

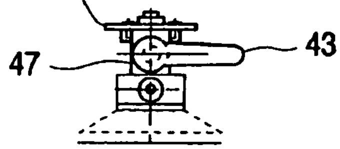


FIG. 3A

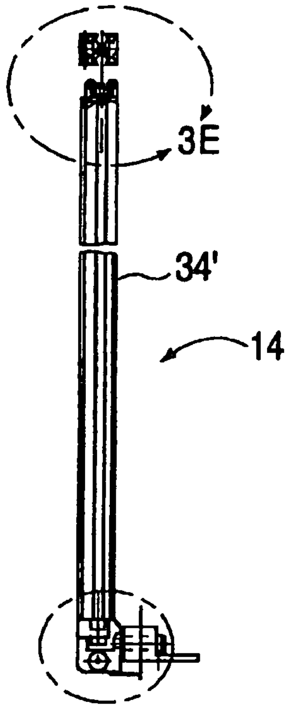


FIG. 3B

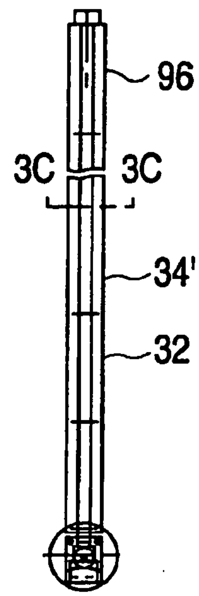


FIG. 3C

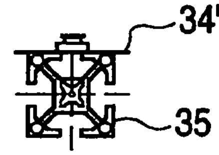


FIG. 3D

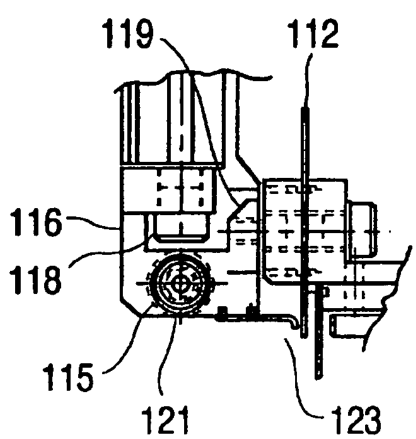


FIG. 3E

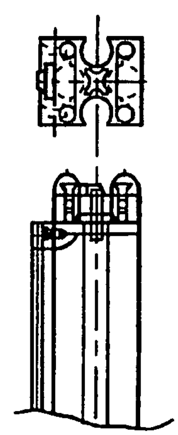


FIG. 4A

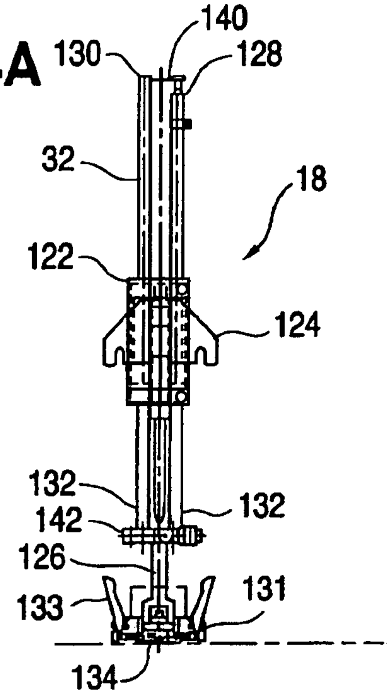


FIG. 4C

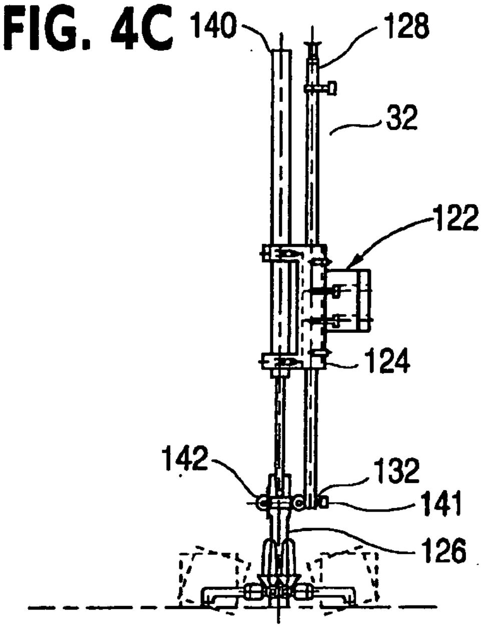


FIG. 4B

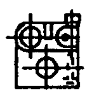


FIG. 4D

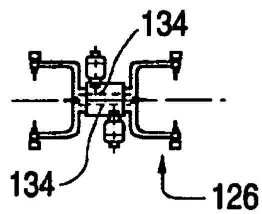


FIG. 4E

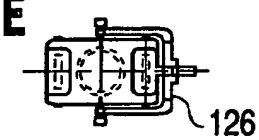


FIG. 4I

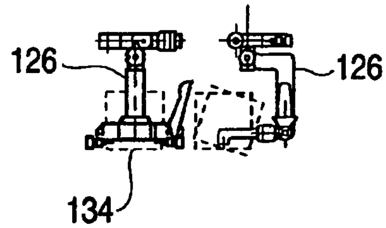


FIG. 4F

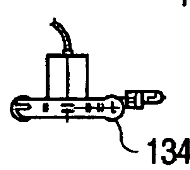


FIG. 4G

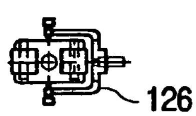


FIG. 4J

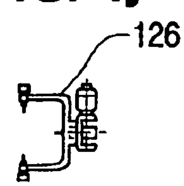


FIG. 4H

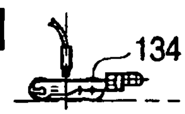


FIG. 5A

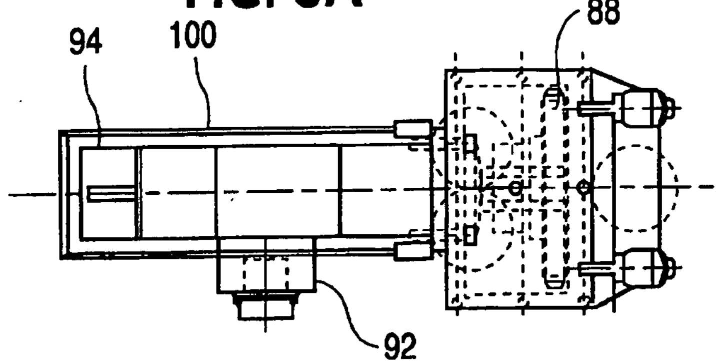


FIG. 5B

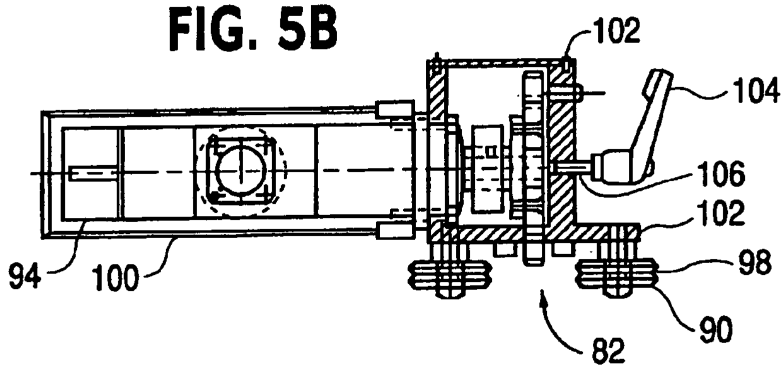


FIG. 5C

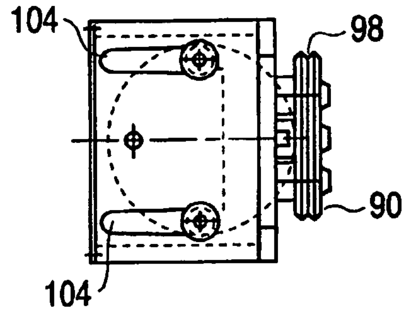


FIG. 5D

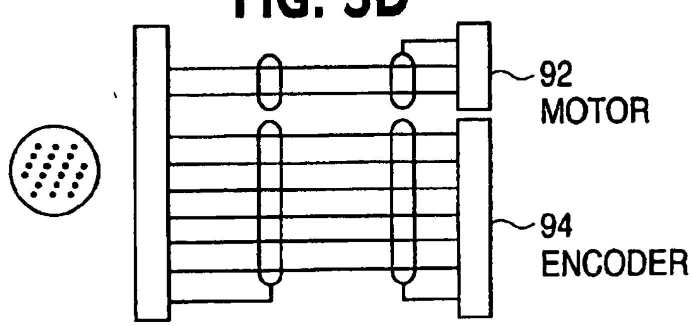


FIG. 6A

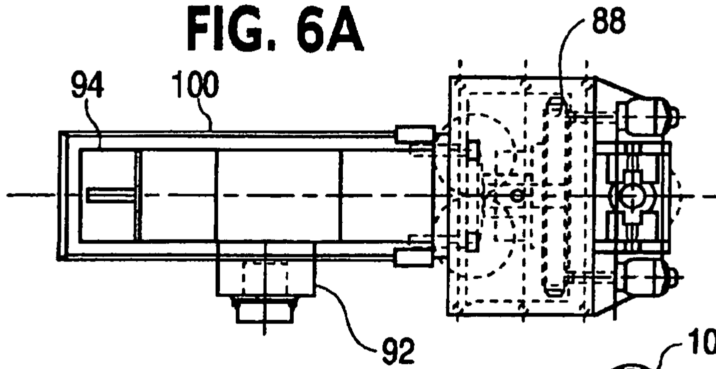


FIG. 6B

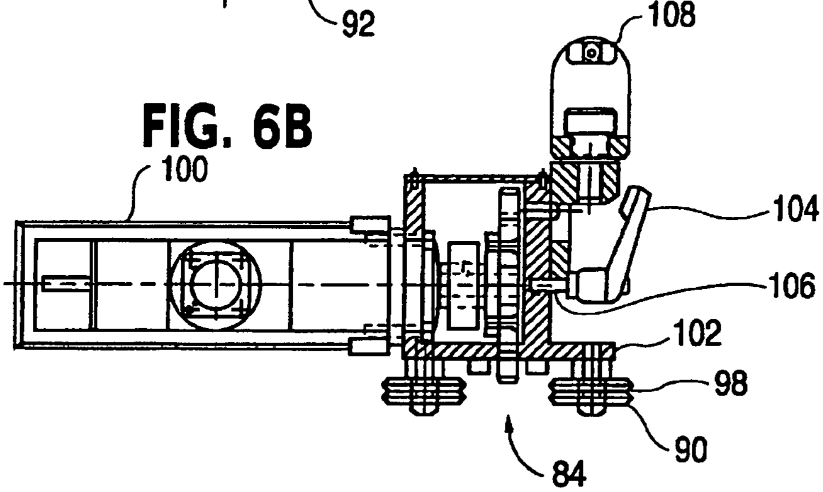


FIG. 6C

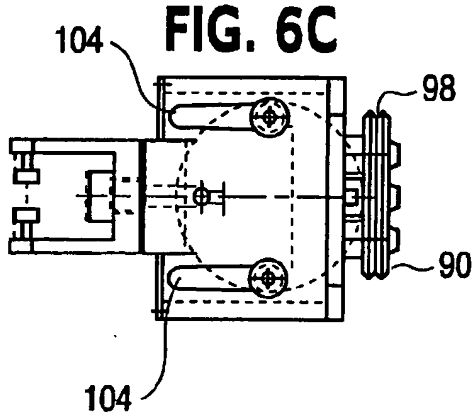


FIG. 6D

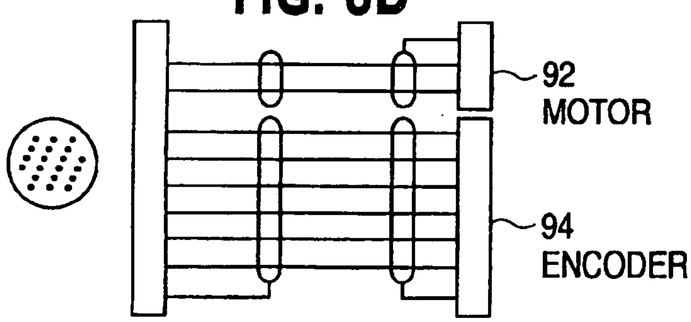


FIG. 7A

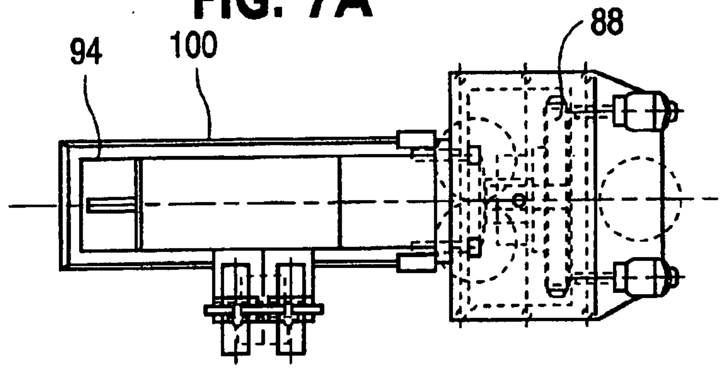


FIG. 7B

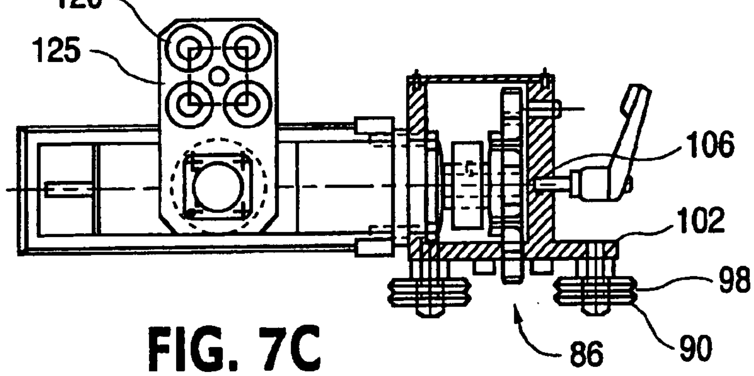


FIG. 7C

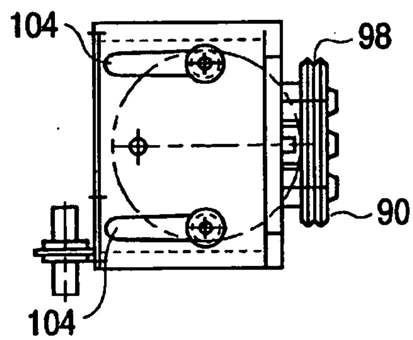


FIG. 7D

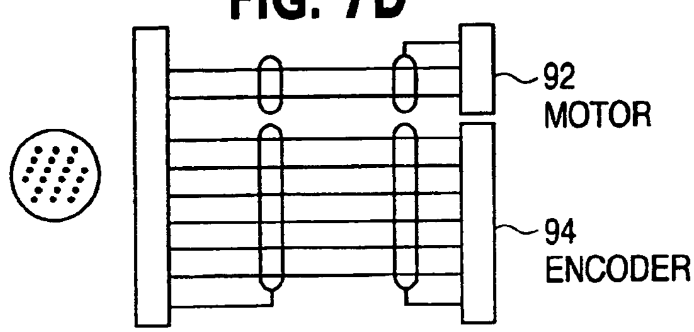


FIG. 8

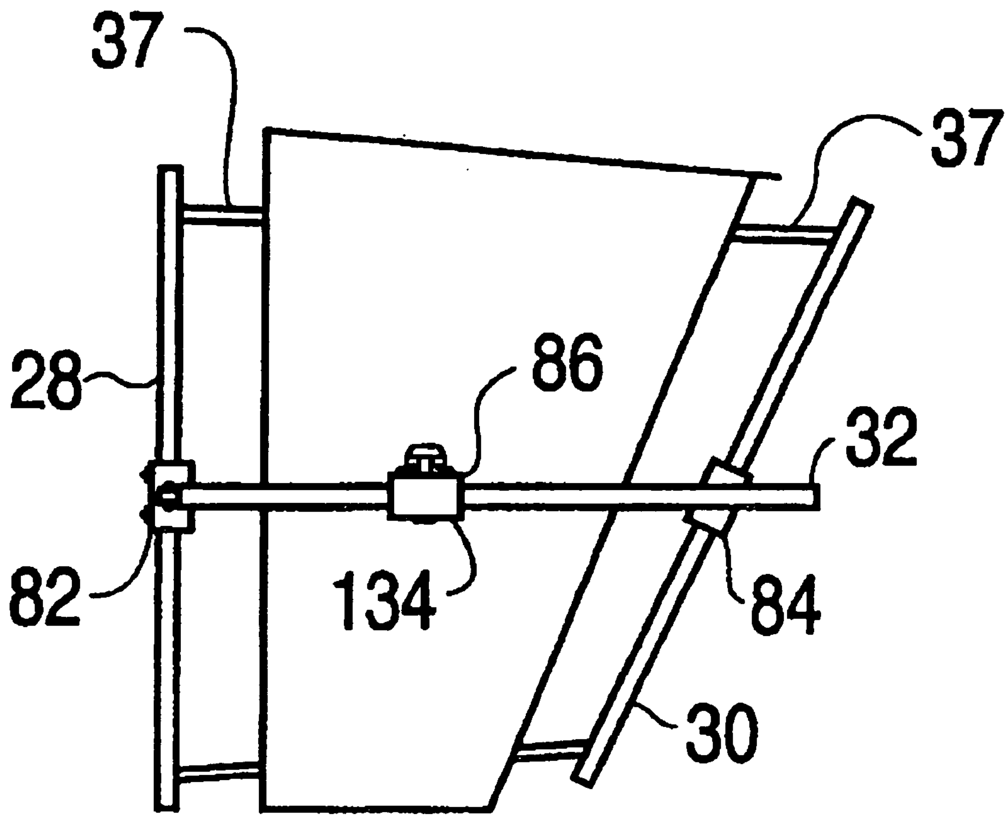
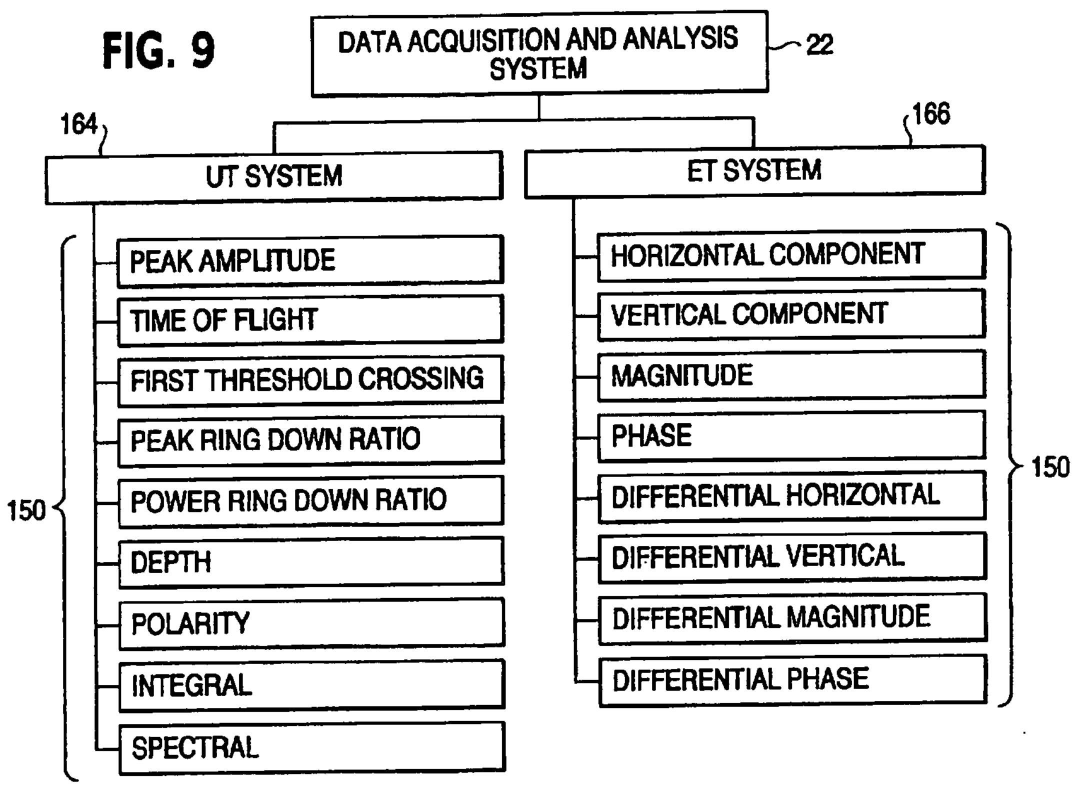


FIG. 9


DATA ACQUISITION AND ANALYSIS SYSTEM
22
164
166
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ET SYSTEM
PEAK AMPLITUDE
TIME OF FLIGHT
FIRST THRESHOLD CROSSING
PEAK RING DOWN RATIO
POWER RING DOWN RATIO
DEPTH
POLARITY
INTEGRAL
SPECTRAL
150
HORIZONTAL COMPONENT
VERTICAL COMPONENT
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DIFFERENTIAL MAGNITUDE
DIFFERENTIAL PHASE
150

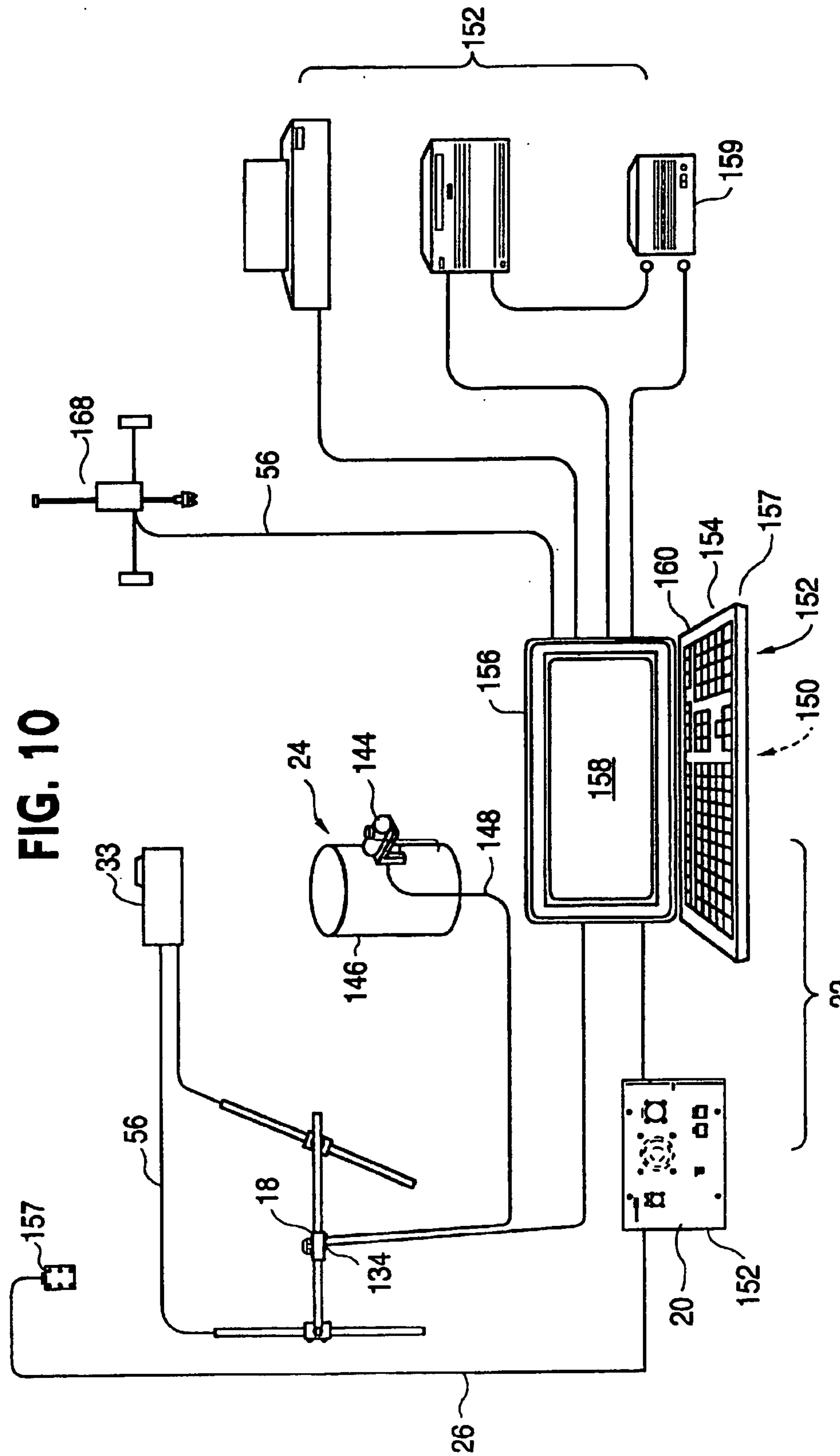
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FIG. 10

APPARATUS AND METHOD FOR PERFORMING NON-DESTRUCTIVE INSPECTIONS OF LARGE AREA AIRCRAFT STRUCTURES

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to and claims the benefit of U.S. Provisional Application No. 60/074,876, filed Feb. 17, 1998 and assigned to the assignee of the application.

FIELD OF THE INVENTION

This invention relates generally to machines for performing non-destructive inspections of large area aircraft structures. More particularly, this invention relates to an aircraft scanner having tracks secured to a surface of a large object, such as an aircraft. Still more particularly, this invention relates to a method and apparatus for manipulating a test probe in a rectilinear scan pattern with a master X-axis, a slave X-axis, and a Y-axis.

BACKGROUND OF THE INVENTION

Multi-axis robotic manipulators, also know as mechanical scanners, are used for performing non-destructive inspections (NDI) of materials in many industries. The designs of such machines vary widely and include X-Y gantry systems, X-Y manipulators, R-THETA manipulators, and Z-THETA manipulators. While the specific designs of such machines vary widely, their theories of operation are similar. Mechanical scanners are used to manipulate a NDI probe in a pre-programmed scan pattern on an inspection surface. An analog signal from the NDI probe is monitored, digitized, and displayed by a data acquisition and analysis system. Position information provided by feedback devices on the scanner is used by the data acquisition and analysis system to develop a two- or three-axis mapping of the NDI information. Typical NDI methods used with this type of machine include ultrasonic testing, eddy current testing, and mechanical impedance testing.

Non-destructive inspections of military and civilian aircraft are currently being performed at various maintenance facilities throughout the United States. Ultrasonic methods and mechanical impedance methods are commonly used to detect disbonds between the outer skin and the honeycomb core in composite aircraft structures such as wings. Such disbonds may be caused by repeated stress reversals or water entrapment within the structures. Eddy current methods are currently being used to detect surface cracking in thin skin aircraft structures such as fuselages. Cracks in the skin commonly develop around fasteners and are caused by repeated stress reversals within the structures.

Most of the NDI of modern aircraft is being performed using manual techniques. These techniques require that a technician manipulate a hand-held probe on the aircraft surface while simultaneously monitoring a NDI instrument. Thus, the quality of manual NDI techniques are highly operator dependent. Moreover, such manual NDI techniques are labor intensive and slow. Still further, NDI data obtained during manual inspections cannot, in general, be saved as a permanent record.

NDI of modern aircraft is currently being performed using a limited amount of automated NDI techniques. Growth in the use of automated NDI methods has been limited due to the complex nature of modern aircraft structures. Typical aircraft surface geometries may be flat, conical, cylindrical,

or some combination of the three representative typical surface geometries. The surface curvatures may be convex or concave, while the surface orientations may be horizontal, vertical, or overhead.

Most on-aircraft automated NDI techniques require the use of a mechanical scanner to manipulate a NDI probe, whether ultrasonic, eddy current, or mechanical impedance, in a preprogrammed scan pattern on the aircraft surface. Various aircraft scanner designs exist. These designs include rigid X-Y gantry systems which are supported by floor-mounted bases or which are mounted to the aircraft surface by vacuum cups. Another common design involves the use of a track-mounted, two-axis scanner. In this type of system, a vacuum track is coupled to the surface of the aircraft structure. A two-axis scanner mounts to the vacuum track via guide rollers or magnetic wheels. The X-axis typically coincides with the track axis. A cantilevered Y-axis is oriented 90 degrees relative to the X-axis.

Conventional mechanical scanner designs have seen limited use in aircraft NDI applications because they are not well-suited to the demands of the task. Conventional gantry systems are well-suited for inspecting large areas with flat surfaces but they cannot be adapted conveniently for small diameter curved surfaces or areas with limited access. Conventional vacuum track-mounted scanners can adapt to both flat and curved surfaces, but they can only cover a narrow area due to the cantilevered Y-axis.

Accordingly, a need has been recognized for a mechanical scanner which can be used to perform non-destructive inspections of large area aircraft structures, which can conform to the complex surface curvatures present on modern aircraft, and which is lightweight, less expensive, and has improved speed capabilities and enhanced flexibility in relation to existing designs.

SUMMARY OF THE INVENTION

Directed to achieving the foregoing and additional objectives and overcoming shortcomings of the prior art systems, a main object of the invention is to provide a scanner which efficiently performs non-destructive inspections of large area aircraft structures.

Another object of the invention is to provide a scanner according to the invention which interfaces to ultrasonic, eddy current, and mechanical impedance NDI probes.

Another object of the invention is to provide a scanner which manipulates a NDI probe in a rectilinear scan pattern when operated under control of a motion control system.

Still another object of the invention is to provide a scanner which conforms to complex surface geometries present on modern aircraft, these surface geometries include flat surfaces, convex curved surfaces, concave curved surfaces, cylindrical surfaces, conical surfaces, and parabolic surfaces.

Another object of the invention is to provide a scanner which operates on horizontal, overhead, and inverted aircraft structures.

A yet further object of the invention is to provide a scanner which couples to aircraft surfaces via an array of vacuum cups.

Still another object of the invention is to provide a scanner which is lightweight, portable, and easily set up by a single operator.

Another object of the invention is to provide a scanner which uses a modular design to facilitate equipment set up on the aircraft.

Another object of the invention is to provide a scanner which combines the large area inspection capabilities of a two-axis gantry system with surface-following and contour-following capabilities of a two-axis track-mounted scanner.

The foregoing and other objects of the present invention are accomplished by providing a scanner with two flexible tracks. Each flexible track is fitted with a motor driven tractor assembly. A rigid beam track spans the two flexible tracks. The rigid beam track spans between the two flexible tracks, and is coupled to each tractor assembly by articulating joints. The articulating joints permit movement at the joints along at least three independent axes.

The rigid beam supports a third motorized tractor. This third tractor supports a compliant thruster assembly that deploys gimbaled mechanical impedance, ultrasonic or eddy current inspection probes. The gimbal positively loads the inspection probes, keeping them in contact with the inspection surface with near constant force.

The rigid beam track serves as the scanner's Y axis. The flexible vacuum tracks serve as the X axis. The Y axis stroke is limited to the length of the rigid beam. The X axis stroke can be made infinitely long by connecting multiple track sections in a chain.

The scanner also includes a data acquisition and analysis system that controls scanner functions and operations. The movement of the scanner is controlled by a scan control subsystem forming part of the data acquisition and analysis system. The scan control system includes both hardware and software for controlling the movement of the scanner over the surface to be inspected. The software includes a teach mode that permits an operator to preprogram the scan pattern for the surface to be inspected using a global coordinate system. The global coordinate system allows the operator to reference points on the surface and the data display using an identical coordinate system.

The scanner may be used to inspect surfaces including complex geometrical shapes. The scanner is particularly adapted for use in inspecting horizontal, overhead, and inverted aircraft surfaces.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and inventive aspects of the present invention will become more apparent upon reading the following detailed description, claims and drawings, of which the following is a brief description:

FIGS. 1A–1D show views of the flexible configuration of the scanner according to the invention, in which FIG. 1A is a top plan view of an assembly of a Y-axis track assembly, an X-axis flexible track assembly, a master X-axis tractor assembly, a Y-axis tractor assembly, a slave X-axis tractor assembly, and a thruster assembly;

FIG. 1B is a side elevational view of the assembly of FIG. 1A, and

FIG. 1C is an end view of the side view of FIG. 1B, and

FIG. 1D is a side elevational view of the assembly of FIG. 1A.

FIGS. 2A–2H show views of of a flexible track assembly for the scanner according to the invention, in which FIG. 2A is a top plan view of a track used in the invention;

FIG. 2B is a side elevational view of the track shown in FIG. 2A;

FIG. 2C is a cross-section taken along line B—B of FIG. 2B;

FIG. 2D are receptively details of the ends of the track shown in FIG. 2B;

FIG. 2E is an end view of the track shown in FIGS. 2B and 2D;

FIG. 2F is a cross-section taken along line A—A of FIG. 2E;

FIG. 2G is a plan view of the flexible track assembly with a flexible vacuum line; and

FIG. 2H is a detailed view of the right end of the track of FIG. 2B.

FIGS. 3A–3E are assembly drawing of a Y-axis track assembly for the scanner according to the invention, in which FIG. 3A is a side view of the Y-axis track assembly;

FIG. 3B is a plan view of the Y-axis track assembly according to FIG. 3A;

FIG. 3C is a cross-section view taken along line D—D of FIG. 3B;

FIG. 3D is a detailed view of one end of the track assembly shown in FIG. 3A; and

FIG. 3E is an expanded view of the other end of FIG. 3A, including an expanded end view of that same end.

FIGS. 4A–4J are assembly drawings of the thruster assembly shown in FIG. 1 for the scanner according to the invention, in which FIG. 4A is a plan view of the thruster assembly,

FIG. 4B is an end elevational view of the end of the assembly of FIG. 4A;

FIG. 4C is a side elevational view of the thruster assembly of FIG. 4A;

FIG. 4D is an end view of an end of the thruster assembly shown in FIG. 4C;

FIG. 4E is a plan view of an optional sled assembly for use with the thruster assembly;

FIG. 4F is a side elevational view of the probe sled assembly of FIG. 4E;

FIG. 4G is a plan view of another probe sled assembly for use with the thruster assembly;

FIG. 4H is a side elevational view of the probe sled assembly of FIG. 4G;

FIG. 4I is a side elevational view of an optional single transducer setup for use with the thruster assembly of FIG. 4; and

FIG. 4J is a side view of the transducer setup of FIG. 4I.

FIGS. 5A–5D are drawings is a drawing of a master X-axis tractor assembly shown in item 3 of FIG. 1, in which FIG. 5A is a top plan view of the subject assembly;

FIG. 5B is a side view, partially in section, of the subject assembly in FIG. 5;

FIG. 5C is an end elevational view of the assembly shown in FIG. 5A; and

FIG. 5D is a wiring diagram for connection the motor and optical encoder shown in FIGS. 5A and 5B.

FIGS. 6A–6D are assembly drawings of the slave X-axis tractor assembly for the scanner according to the invention, in which FIG. 6A is a top view of the subject assembly;

FIG. 6B is a side view, partially in section, for the assembly shown in FIG. 6A,

FIG. 6C is an end view of the assembly shown in FIG. 6A; and

FIG. 6D is a wiring diagram for connecting the motor and encoder as shown in FIGS. 6A and 6B.

FIGS. 7A–7D are assembly drawings of the Y-axis tractor assembly of FIG. 1 in which FIG. 7A is a top view of the subject assembly;

FIG. 7B is a side view, partially in section, for the assembly shown in FIG. 7A;

FIG. 7C is an end view of the assembly shown in FIG. 7A; and

FIG. 7D is a wiring diagram for connecting the motor and encoder as shown in FIGS. 7A and 7B.

FIG. 8 is an assembly drawing of the scanner of FIG. 1 showing the master and slave X-axes offset by surface fixturing.

FIG. 9 is a block diagram of the scanner of FIG. 1 showing the analysis and software features of the data acquisition and analysis system.

FIG. 10 is a system diagram of the scanner of FIG. 1 showing the interrelation of major system components

DESCRIPTION OF THE PREFERRED EMBODIMENT

The scanner 10 enables an operator to perform nondestructive inspection (NDI) of a wide variety of surface types. The scanner 10 shown in FIGS. 1–10 includes three interrelated track assemblies. These track assemblies separately include several common elements. It will be understood that common reference numerals are used to describe common features of the embodiment of the scanner shown in FIGS. 1–10.

FIG. 1 shows a scanner 10 formed according to the present invention. The scanner 10 includes a vacuum track assembly 12, a Y-axis track assembly 14, a tractor assembly 16, a thruster assembly 18, a scan control subsystem 20, a data acquisition and analysis system 22, a couplant supply system 24, a vacuum supply system 33, and an umbilical cable assembly 26. To prevent damage to the identified components, the scanner 10 may be tethered to an external device to prevent the scanner 10 from falling should it become detached from the inspection surface. The exposed components of the aircraft scanner 10 are fabricated of a corrosion resistant material or are adequately corrosion protected. However, it will be appreciated that other materials may be selected.

The vacuum track system 12 couples the scanner 10 to the surface to be inspected. As illustrated in FIG. 2, the vacuum track system 12 includes a master X-axis vacuum track assembly 28 and a slave X-axis vacuum track assembly 30. It will be understood that the X- and Y-axes orientations refer to the generally known X-Y coordinate system. However, the track assemblies 28, 30 and 32 (discussed below) are designed to permit various angular and linear orientations relative to the X-Y coordinates of the surface to be inspected. For instance, in one embodiment of the scanner 10, the master X-axis assembly 28 and the slave X-axis track assembly 30 are spaced apart in a vertical orientation. As the X-axes track assemblies 28, 30 are configured in a master-slave relationship, the lengths of the X-axes vacuum track assemblies 28, 30 do not have to be in parallel alignment.

It will be appreciated that the master X-axis 28 and the slave X-axis 30 each include common features, and thus are discussed jointly using common reference numerals to describe common features. The X-axes vacuum track assemblies 28, 30 each includes at least one track plate 34 section, which forms the primary support surface for the vacuum track assemblies 28, 30, and an array of vacuum cups 39, and an end of travel hard stop mechanism 36.

The track plates 34 can be used singly or interconnected as discussed above. An indefinite number of track plate 34 sections may be coupled together to form the desired track length. The track plates 34 have an overall length of four feet, and are fabricated using a thin gauge spring steel. It will be appreciated that various lengths and other appropriate materials may be used. The flexible track plates 34 do not yield or plastically deform upon bending and twisting, if necessary, to adapt the track plates 34 to the curvature of the surface to be inspected. The vacuum track plates 34 may be adjusted to mate with horizontal, vertical, overhead, conical, cylindrical, flat, concave, convex and compound curved surfaces or any combination of the aforementioned surfaces. In particular, the track plates 34 are especially adapted to conform to curved surfaces typically found on an aircraft fuselage, wing and engine support structures such as cowls.

The track plates 34 support an array of vacuum cups 39. The array of vacuum cups 39 includes a plurality of vacuum cup assemblies 38, at least two end vacuum cup assemblies 42, and at least one control vacuum cup assembly 44. The number of vacuum cup assemblies 38 used per unit track 28, 30 length varies depending on the size of the surface to be inspected and the number of track plates 34 needed. However, the number of vacuum cups 38 used should provide for a smooth track curve that approximates the curvature of the surface to be inspected.

The embodiment illustrated in FIG. 2 shows one end cup assembly 42 positioned on each end 62, 63 of the vacuum track assemblies 28, 30. Positioned between the two end cup assemblies is a plurality of vacuum cup assemblies 38. FIG. 2 also shows the control cup assembly 44 positioned on the track assembly 28, 30 between one end cup assembly 42 and the first vacuum cup assembly 38*a*.

Each vacuum cup assembly 38, 42 and 44 includes a housing 46, 47 and 48, respectively. A mechanical fastener such as a screw couples each housing 46, 47 and 48, respectively, to the track plate 34. Each housing 46, 47 and 48 supports a mounting hinge 40 for coupling each vacuum cup assembly 38, 42, and 44 to the respective housing 46, 47 and 48. The mounting hinge 40 permits positioning the vacuum cup assemblies 38, 42 and 44 at various angular orientations. Each housing 46, 47 and 48 also supports an adjustable handle 43 for positioning the vacuum cup mounting hinge 40 in the desired orientation.

This angular adjustment feature permits the X-axes vacuum track assemblies 28, 30 to be mounted onto conical or irregular surfaces as discussed above. In one embodiment, the mounting hinge 40 permits adjusting each vacuum cup assembly 38, 42 and 44 to an angular position between zero and thirty degrees relative to the respective vacuum track assembly 28, 30. It will be appreciated that other angular settings are possible. Such an adjustment permits the X-axes vacuum track assemblies 28, 30 to mate with surfaces having small diameters.

With respect to the vacuum cup assembly 38, the housing 46 defines an opening 54 extending therethrough. Each side of the opening 54 receives a barbed fitting 58 that extends outwardly from the opposite sides of the vacuum cup assembly 38. However, the opening 54 of the first vacuum cup 38*a* receives the barbed fitting 58 only in the portion of the opening 54 facing the array of vacuum cup assemblies 38. The opposite side of the opening 54 for the vacuum cup 38*a* receives a close nipple 66 that prevents air at ambient pressure from flowing into the vacuum cup 38*a*.

Each barbed fitting 58 supports a length of tubing 56. Together the tubing 56 and the vacuum cup assemblies 38, 42 and 44 create a pneumatic circuit such that the tubing 56 serially couples the vacuum cup assemblies 38, 42 and 44 to

an external vacuum source 33 (discussed below). Specifically, the vacuum cup assemblies 38, 42, and 44 of each four-foot track plate 34 section are independently plumbed to the vacuum source 33. Consequently, a failure in one track plate 34 segment will not cause other segments to fail.

Turning now to the end cup assemblies 42, the housing 47 defines an opening 50. One side of the opening 50 receives the barbed fitting 58 and tube 56 assembly. A hex plug 60 caps the other side of the opening 50. At the end 63 of the track assembly 28, 30, the tubing 56 couples the end cup assembly 42 to an adjacent vacuum cup assembly 38. At the opposite end 62, the tubing 56 couples the other end cup assembly 42 to the control cup assembly 44.

With respect to the control cup 44, the housing 48 defines an opening 52. One side of the opening 52 receives an air valve 64 that couples the vacuum control cup 44 to a source of vacuum pressure via tubing 68. The other side of the opening 52 receives a close nipple 66 that prevents air at ambient pressure from entering the opening 52. Additionally, each housing 46, 47 and 48, respectively, supports a vacuum cup mounting bracket 70. The mounting bracket 70 supports a flexible cup-shaped vacuum pad 76. The vacuum pad 76 mechanically couples to the mounting bracket 70 using known techniques such as screw threads or other similar methods. Additionally, the mounting bracket 70 defines an opening 72. The opening 72 is in fluid communication with openings 54, 50 and 52, respectively, and is covered by an end cap 74.

The vacuum pad 76 surrounds the end cap 74, and provides a soft smooth surface that physically engages the surface to be inspected. For instance, when vacuum pressure is applied to the vacuum cup assemblies 38, 42 and 44, a suction force is induced through the end cap 74 into the open center formed by the vacuum pad 76. This force causes the vacuum pad 76 to adhere to the surface to be inspected.

The vacuum pressure applied to the vacuum pad 76 is sufficient to permit the vacuum cup assemblies 38, 42 and 44 to form leak proof seals with rough as well as smooth surfaces. It is possible, however, that the integrity of the surface may not permit a vacuum tight seal between the vacuum cup assemblies 38, 42 and 44 and the surface under inspection. Consequently, the leakage of up to two vacuum cup assemblies 38, 42 and 44 each four foot track plate 34 section generally does not affect overall vacuum track 28, 30 coupling to the surface being inspected. It will be appreciated, however, that the number of vacuum cups 38, 42 allowed to leak during the inspection process may vary depending on the size of the vacuum pump and cups used.

An electric vacuum pump (not shown) induces a vacuum pressure at the vacuum cup assemblies 38, 42 and 44. In one embodiment, the vacuum pump is rated for 110–120V AC power, and is rated for explosion proof service in accordance with the National Electric Code, Article 500, Class, Group D locations, said standard incorporated herein by reference. The pump has sufficient capacity to provide the required coupling force for both the master X-axis 28 and the slave X-axis 30 vacuum cup assemblies 38, 42 and 44.

In the event the vacuum tracks 28, 30 are too long for the surface to be inspected, the excess vacuum cups 38, 42 are capped using known techniques. To further facilitate single operator loading of the scanner 10 onto the surface to be inspected, an audible warning system (not shown) alerts the operator of possible vacuum cups 38, 42, 44 decoupling. The audible warning is activated upon detection of a partial loss of vacuum.

Finally, the X-axes vacuum track assemblies 28, 30 include an end of travel hard stop mechanism 36 supported by the distal ends 62, 63 of each vacuum track assembly 28, 30. The hard stop prevents the X-axes tractors 82, 84 (discussed below) from running off the ends of the tracks 28, 30. The motor current limits in the scan control subsystem 20 interrupt power if a tractor 82, 84 is driven into a hard stop 36.

Turning now to a description of the X-axes tractor assemblies 82, 84, as illustrated in FIGS. 5–6, each track assembly 28, 30 supports separate tractor assemblies 82, 84. Together, the master X-axis tractor 82/track 28 assembly, including one section of track 28, 30, inclusive of fixturing, position sensors, and drive components, form a lightweight assembly. Additionally, the X-axes tractors 82, 84 have an axis repeatability capability that permits certain locations to be returned to repeatedly with minimal error. Additionally, the X-axes tractors 82, 84 include axis position resolution capabilities.

Each tractor assembly 82, 84 includes a pinion gear 88, and a plurality of V-shaped guide rollers 90. In one embodiment, separate gear assemblies couple the respective tractor assemblies 82, 84 to the respective track assembly 28, 30. To that end, the track plate 34 receives and supports a lightweight gear rack 96. The gear rack 96 is bonded to the track plate 34 such that the gear contacting face of the gear rack 96 is oriented face-up on the top surface of the track plate 34.

The gear rack 96 is designed in accordance with conventional standards, and receives a pinion gear 88 supported by the tractor assembly 82, 84, respectively. Each pinion gear 88 engages the gear rack 96 of the respective vacuum tracks 28, 30, forming a slip-free drive engagement. This arrangement, thus, forms a rack and pinion drive system capable of precision movement and positioning.

To facilitate the achievement of the slip free drive arrangement, the pinion gear 88 is motor driven. The driving motor 92 is a DC servo gear motor that mechanically couples the pinion gear 88 using conventional techniques. In the disclosed embodiment, a motor can 100 supports the motor 92, and the motor 92 is rated for explosion proof service in accordance with the National Electric Code, Article 500, Class 1, Group D, said standard incorporated herein by reference, or optionally certified per ML-M-8609, incorporated herein by reference.

A housing 102 retains both the motor 92 and the supporting motor can 100. The exterior surface of the housing 102 supports a plurality of V-shaped guide rollers 90. The V-shaped contacting surface 98 of the guide rollers 90 engages the edges of the respective X-axes 28, 30 track plates 34 in a way that the respective track plates 34 act as linear guides and the V-shaped guide rollers 90 act as linear bearings that facilitate the movement of the tractor assemblies 82, 84 along the X-axes tracks 28, 30. Thus, this arrangement further enhances the slip-free mechanical engagement between the respective tractor assemblies 82, 84 and the track assemblies 28, 30.

The housing 102 also supports at least one clamping handle 104 on the housing's 102 exterior surface. The clamping handle 104 supports a threaded shaft 106. Each shaft 106 of the respective tractor assembly 82, 84 housing 102 is received by a threaded surface supported by each track assembly 28, 30. The shaft 106, manipulated by the clamping handle 104, thus couples the respective tractor assembly 82, 84 to the respective X-axes track assembly 28, 30.

The clamping handle 104 functions similarly to a screw; however, the clamping handle 104 may be adjusted without the use of a separate tool, e.g., a screwdriver. The clamping handle 104 thus permits quick connect/disconnect of the tractor assemblies 82, 84 to/from the respective track assembly 28, 30.

To aid in determining the accuracy of the selected location, each tractor assembly 82, 84 includes at least one optical encoder 94 for position feedback accuracy. As shown in FIGS. 5D and 6D, the motor 92 and the encoder 94 are electrically wired using standard wiring techniques.

In addition to the aforementioned components, the slave X-axis tractor assembly 84 includes a position adjustment mechanism 108. The position adjustment mechanism 108 through appropriate mechanical fixturing is coupled to the housing 102. As illustrated in FIG. 6, slide bearing pin screws may be used in coupling the position adjustment mechanism 108 to the Y-axis track assembly 32. Together, this coupling arrangement and the position adjustment mechanism 108 permit the slave X-axis 30 to move along three axes relative to the Y-axis 32.

Turning now to FIG. 3, the Y-axis track assembly 14 is shown. It will be appreciated that the Y-axis track assembly 14 and the X-axis track assembly 12 share common elements. Thus, common reference numerals are used to describe the common features. The flexible track assembly 14 includes at least one track plate 34', a rigid strut 35, an angle dial plate 112, and a master mounting bracket 116. The track plate 34' is fabricated of a flexible material such as spring steel. However, it will be apparent that the choice of material may vary depending on the desired level of flexibility. The track plate 34' is coupled to the rigid strut 35 by mechanical fasteners such as screws.

The Y-axis track assembly 32 has a linear stroke of six feet. However, shorter track lengths may be used, particularly for scanning in confined areas. When assembled as a unit, the track assemblies 28, 30 and 32 permit scanning the surface under inspection to the track edges. To facilitate scanning up the partedges, vacuum coupled fixturing 37, as shown in FIG. 8, offsets the master and slave X-axes 28, 32 from the edges of the surface to be inspected.

As shown in FIGS. 1 and 3, the Y-axis track assembly 32 extends between the master X-axis track assembly 28 and the slave X-axis track assembly 30 such that the master X-axis tractor assembly 82 supports one end 78 of the Y-axis track assembly 32 and the slave X-axis tractor assembly 84 supports the opposite end 80. Additionally, the Y-axis track assembly 32 may overhang the X-axes tracks 28, 32. The Y-axis track assembly 32 need not extend perpendicularly to the X-axes 28, 30, particularly since the articulating joints coupling the Y-axis track assembly 32 and the X-axes tracks 28, 30 include multiple degrees of freedom.

The articulating joints accommodate non-parallelism and twist of the X-axes vacuum track assemblies 28, 30. Such an arrangement permits adjustment of the track assemblies 28, 30 and 32 to mate with surfaces of various configurations. In one embodiment, the articulating joints permit movement of the X-axes 28, 30 and the Y-axis 32 along three axes: altitude, azimuth and twist. These articulating joints may be established using appropriate quick connect/disconnect couplers and fasteners.

To accommodate movement along the three axes of movement, the end 78 supports a master mounting bracket 116 that supports an angle dial plate 112 and a pivot mechanism 115. The angle dial plate 112 is marked in gradients ranging from zero to 360 degrees. The angle dial plate 112 may be rotated to the desired angular position, and an indicator 123 visually marks the selected position. Thus, the angle dial plate 112 permits adjustment of the angular orientation of both the Y-axis track assembly 32 relative to the master X-axis assembly 28, as the master mounting bracket 116 supports both the Y-axis track 32 and the master X-axis track 28.

The Y-axis track assembly 32 and the master X-axis track assembly 28 are supported by the pivot mechanism 115 of the master mounting bracket 116. The pivot mechanism 115 is a U-shaped member forming an upper pivot block 118 and a lower pivot block 119. A bushing 121 supported by the pivot mechanism 115 permits slight movement of both the upper and lower pivot blocks 118, 119. Consequently, rotating the dial plate 112 causes movement of the upper and lower pivot blocks 118, 119, thus resulting in a relative change in position of both the Y-axis track assembly 32 and the master X-axis track assembly 28, respectively.

The Y-axis track 32 supports a gear rack 96 for receiving a pinion gear 88 supported by the Y-axis tractor assembly 86. This arrangement forms a rack and pinion arrangement, as described above for the X-axes tractor assemblies 82, 84. Except as otherwise specified, the Y-axis tractor assembly 86, shown in FIG. 7, includes each component previously described for the X-axes tractor assemblies 82, 84. Consequently, the previous discussion of the X-axes tractor assemblies 82, 84 sufficiently describes the components and general function of the Y-axis tractor 86.

In addition to the aforementioned components, the Y-axis tractor assembly 86 includes a BNC connector array 120. A plate 125 carried by the motor can 100 supports the BNC connector array 120, and the connectors are bulkhead BNC connectors.

As shown in FIGS. 1 and 4, the Y-axis track 32/tractor 86 assembly support a thruster assembly 18., A thruster bracket 122 couples the thruster assembly 18 to the Y-axis track 32/tractor 86 assembly using mechanical fasteners. The thruster assembly 18 may be placed on either side of the Y-axis track assembly 32.

The thruster bracket 122 supports a thruster slide block 124 and a gimbal 126. The thruster slide block 124 permits the thruster assembly 18 to move along the Y-axis track 32. Two shafts 128, 130 movably support the thruster slide block 124. The shafts 128, 130 extend in the same direction, and provide the surface over which the thruster slide block 124 travels.

The proximate end 132 of the shafts 128, 130 support the gimbal 126, which supports the nondestructive inspection (NDI) probes 134 that actually scan the surface to be inspected. The gimbal 126 extends outwardly from shafts 128, 130, and possesses at least two axes of movement. The gimbal 126 includes one or more outwardly extending prongs for supporting the NDI probes 134, which may or may not include probe sleds.

The gimbal 126 may be equipped with mechanical impedance, ultrasonic or eddy current NDI probes 134. For example, the NDI probes 134 may include a single transducer probe 134 as shown in FIGS. 4I and 4J, an ET probe sled assembly as shown in FIGS. 4G and 4H, or an ET probe sled assembly 138 as shown in FIGS. 4E and 4F. The transducer probes 134 used may include (1) one or two ultrasonic transducers with integral couplant feed; (2) one or two eddy current probes; or (3) one transducer with couplant feed and one eddy current probe.

The thruster assembly 18 provides for loading standard ultrasonic shear and longitudinal transducers having select-

able crystal sizes appropriate to perform the function of the scanner **10**, and eddy current surface probes with appropriate case diameters. It will be appreciated that other transducers and probes may be used. For instance, the gimbal **126** is capable of interfacing and scanning with other types of NDI probes such as those used in low frequency bond testing. However, care should be taken to maintain compatibility among the sensors, particularly with respect to length, diameter, and weight.

Clamping handles **131**, **133** couple the NDI probes **134** to the gimbal **126**. The clamping handle **131** permits adjustment of the angle of the NDI probe **134** along a 360° arc. The second handle **133** permits quick connect/disconnect of the coupling to the gimbal **126**.

The gimbal **126** positively loads the NDI probes **134** to the surface under inspection. The positive load is provided by a gas spring **140**. The gas spring **140** is of a conventional type, and applies a constant pressure to the end of the gimbal **126** to ensure full sensor contact with the surface under inspection.

The gas spring **140** provides a simple and effective means for facilitating movement of the NDI probes **134** smoothly over typical aircraft surfaces comprising multi-layer chipped paint, improperly installed countersink fasteners (which can be either protruding or recessed), skin dents, offset skin panels at interfaces and skin external repair doublers. The use of the gas spring **140** in conjunction with the disclosed gimbal **126** design dampens out possible NDI probe **134** oscillations as the probe traverses surface defects. In one embodiment, the constant pressure gas spring **140** helps the sensors negotiate abrupt offsets up to 0.125 inches.

An interface block **142** couples the shafts **128**, **130** and the gas spring **140** to the gimbal **126**. The interface block **142**, thus, serves as a dampening mechanism. Additionally, the interface block **142** includes an clamping handle **141** having a threaded shaft that permits quick connect/disconnect coupling of the interface block to the end **132** of the shafts **128**, **130**.

The scanner **10** includes a portable couplant delivery system **24** for delivering coolant fluid to the ultrasonic probes during ultrasonic scanning operations. The primary couplant delivery **24** components include a delivery pump **144**, couplant supply container **146**, couplant filter (not shown) and required tubing **148**. The delivery pump **144** directs couplant, water, from a supply tank **146** through tubing **148** and into irrigation ports leading to the ultrasonic transducer probes **134** on the scanner **10**.

The delivery pump **144** provides a continuous, constant velocity couplant flow to the transducer **134** face. A variable speed drive motor powers the delivery pump **144**. The drive motor is rated for explosion proof service in accordance with National Electric Code, Article 500, Class 1 Group D, incorporated herein by reference.

The filter removes particles that could reduce the performance of the ultrasonic inspection sequence. In one embodiment, the filter is supported by the inlet to the delivery pump **144** to prevent plugging of the delivery tubing and transducer **134** irrigation ports by dirt particles in the supply water. The filter provides for sufficient couplant flow throughout the operating period. However, the filter may need to be cleaned periodically to ensure efficient operation.

Control of couplant runoff is provided by passive hardware such as flexible strips or gutters. In a non-recirculating couplant delivery system **24**, the flexible strips channel the majority of the spent couplant water from the inspection area by gravity via drain tubes into a collection container. However, if a recirculating system is used, the couplant is directed to the ultrasonic scanner probes using a closed-loop system, wherein the couplant is circulated back to the supply tank **146**.

The tubing **148** used to connect the components of the couplant delivery system **24** is relatively flexible, and sized to deliver a sufficient amount of couplant fluid to the transducers **134**. To that end, the couplant delivery system **24** is configured using known standards and techniques.

The analog signal from the NDI probes **134** is digitized and stored by an external data acquisition and analysis system **22**. The data acquisition and analysis system **22** includes hardware and software subsystems **152**, **150** for controlling scanner **10** operation.

The hardware subsystem **152** includes a portable computer **154** as the host computer. The computer **154** serves as the master computer for the scanner **10**. An operator using a pointing device **157** such as a mouse or a keyboard **160** activates pull down menus, which are displayed on the computer screen **158**. These menus include software files for controlling scanner **10** operations.

The computer **154** includes a CPU board including an Intel 486 DX2/66 MHz microprocessor and 64 Mb of RAM. The computer **154** is coupled to an uninterruptible power supply **159** that prevents the loss of data due to an AC power failure. When activated, the uninterruptible power supply **159** provides power to the computer **154** for a sufficient period of time to allow for a controlled shutdown of the computer **154**.

The computer **154** also includes a ruggidized outer chassis **156** that encloses many components of the data acquisition and analysis system **22** hardware and software subsystems **152**, **150** (discussed below).

The chassis **156** includes a fold-down front panel that includes a panel display **158** and a keyboard **160**. The components forming the display unit include a VGA color display having a suitable resolution. For instance, the resolution may be 640x490 pixels. The display **158** is free from parallax and resolution/color fade when viewed at wide off-axis angles. The keyboard **160** is splash proof. As the keyboard **160** is included in the fold-down-front panel of the chassis **156**, the keyboard **160** is up when not in use. The keyboard **160** forms part of the chassis **156** enclosure case, and provides protection for the panel display **158** when in the non-use position.

The chassis **156** also supports a pointing device **157**. The pointing device **157** is a glidepoint-type structure for use with the graphical user interface. Additionally, the chassis **156** provides power to the axes of the scanner **10**, and it supports connections for a joystick **157'** for manual control and an emergency stop button. The chassis **156** also includes a port for connecting to an external VGA monitor, a minimum of one parallel port, two RS 232 ports, and at least one SCSI interface for data transfer and external data storage. The parallel port may be a Centronics port, and one serial port is dedicated to the pointing device. To facilitate data transfer, the chassis **156** supports hardware for modem or LAN data transfer. In one embodiment the modem has a 14.4K BAUD rate.

Additionally, the chassis **156** supports a data storage means. The data storage means includes an internal storage device such as RAM memory or an external device such as a floppy disk drive or a combination of an external storage device and an internal memory device, each having sufficient memory capacity to perform the NDI effectively. In

one embodiment, the data acquisition and analysis system 22 includes a 1.44 Mb 3.5 floppy disk drive in combination with a 500 Mb internal hard drive, and an external 1 Gb read/write optical drive for system backup and permanent data storage and archival. It will be appreciated that the size of the data storage means may vary depending on system constraints.

The data acquisition and analysis system 22 can store the digitized RF waveform, peak and time-of-flight, and display the data along with the positional information. Stored data and processed information may be output using a printer 155 coupled to the host computer 154. One type of printer 155 that may be used is a Hewlett Packard™ 1200C color printer having at least 4 Mb RAM or equivalent.

Located within the computer 154 chassis 156 are additional components of the data acquisition and analysis system 22 hardware subsystem 152 (discussed below). Test parameters are programmed onto relevant hardware subsystem 152 components, and the programmed parameters control the scanning operation and the ultrasonic and eddy current subsystems.

One additional component of the hardware subsystem 152 is the scan control subsystem 20. The scan control subsystem 20 includes a multi-axis scan control board 162 and appropriate software (discussed below) for controlling the movement of the scanner 10. The scan control board 162 provides coordinated control of the movement of the scanner 10. The scan control board 162 has a master-slave capability that controls and monitors the X-axes tractor 82, 84 drive motors in a master-slave relationship. The scan control board 162 accepts download of scan parameters from the host computer 154 and provides the appropriate signal outputs to the respective DC servo motor 92 amplifier module. The signal output from the motor 92 amplifier module generates the correct drive voltages/current applied to each respective drive motor 92.

The motion control portion of the scan control subsystem 20 is configured on a daughter board of the data acquisition and analysis system 22. The corresponding servo amplifiers are mounted inside a separate electronics enclosure and electrically interfaced between the data acquisition and analysis system 22 and the scanner 10 with quick disconnect cables.

The scan control subsystem 20 operates in a closed loop format and is compatible with the data acquisition and analysis system's 22 ultrasonic pulse on position capability. Additionally, during data gathering or during post inspection data analysis, the scan control subsystem 20 causes the NDI probes 134 to traverse the surface under inspection using operator specified parameters.

During calibration, the operator uses the scan control system 20 to define the scan size, X and Y axes, and the scan grid resolution. As the scanner 10 can be used to inspect surfaces having various geometric configurations, the relative index/speed ratio between the master X-axis 28 and the slave X-axis 30 is variable and automatically determined during the teach mode (discussed below). The ratios established during the teach mode shall remain fixed during actual inspection scanning.

The operator enters the selected values directly or through a teach-and-learn technique. Using the teach-and-learn technique, the operator positions the scanner 10 at the starting point (0,0) and at each respective corner of a parallelogram, thus defining the overall scan area and shape. For example, during the teach-and-learn mode, the operator enters the global X-axis grid spacing and the global Y-axis grid spacing. The data acquisition and analysis system 22 then overlays onto the surface being inspected a global grid of the desired spacing and traverses the grid in 3-axes coordinated motion always staying on the global grid lines. Some benefits of this data recording method include:

- C-scan displays that reflect true shape of scanned areas without pixel mapping losses that can be caused when attempting to display non-rectangular screen.
- Data from the scans is rectilinear and in the same coordinate system so printouts are directly comparable.
- Data from multiple scans is easily displayed in a merged display without data loss due to coordinate rotations.

For example, using the teach-and-learn technique of the present invention, the operator selects inspection area vertices defining the inspection area boundaries. The operator drives the NDI probe 134 to the scan start point, end point and required inspection area vertices using the joystick 157 or other device that provides for simultaneous axis 28, 30, and 32 movement. At each of these points/vertices, the operator enters the axis coordinates. Specific information entered by the operator includes the angle of the Y-axis track 32 relative to the master X-axis 28, the angle the master X-axis 28 makes relative to the global coordinate system reference point. The operator may also specify a target location and move the scanner 10 to that position, and assign a value to the scanner position. This feature allows the operator to reference the position encoder to the global coordinate system (discussed below).

The operator defines the common global coordinate system by identifying and selecting a local origin on the surface to be inspected. The global coordinate system, thus, provides reference to an identical coordinate system laid-out on the scanner 10 display 158. This enables the operator to determine the location of areas suspected of having defects in terms of the global coordinates of the scanned image or the global coordinates of the actual surface under inspection. Thus, the global coordinate system permits referencing points on the surface under inspection and the displayed image using an identical coordinate system.

Using the operator selected input, the scan control subsystem 20 manipulates the aircraft scanner over the surface, executing the taught, preprogrammed, scan pattern, and formulates the appropriate raster scan plan based on the operator selected maximum axis index distance (axes can index less than but never greater than this distance). The selectable maximum axis scan index distance is mapped out using appropriate increments. In one embodiment, the maximum axis scan index distance is set down to 0.005 inches in 0.005 inch increments or greater.

For instance, by employing the teach-and-learn technique, the scanner 10 is configured to scan complex geometrical shapes. For illustration purposes, the teach-and-learn will be explained for three and four sided polygons. These polygons may include interior angles ranging between 30 degrees and 150 degrees. Programming the scanner 10 to scan three sided polygons requires the operator to complete the following steps. First, the operator must define a global coordinate system (discussed below) from which other measurements are referenced. Second, the operator marks the form field "use global coordinate system" to TRUE, and enters on the form field the X and Y offset of the current scanner 10 origin relative to the global coordinate system. The operator also enters the angle of the scanner 10 master X-axis track 28 makes relative to the global coordinate system. Third, the operator enters the angle the Y-axis track 32 makes relative to the scanner 10 master X-axis track 28 for the first scan stroke. Fourth, the operator drives the scanner 10 using the

joystick **157'** to the scan starting location, local origin, and presses a button indicating to the system that this is the local origin. The X-axis and Y-axis encoder position is zeroed at this location. Fifth, the operator manipulates the scanner **10** using the joystick **157'** so that the transducer **134** is at the end of the first stroke along the Y-axis track **32** and presses a button on the screen indicating the current position. The current Y-axis **32** position is read and used as the length of that side of the polygon. The slave X-axis **30** encoder is zeroed at this location. At this point, two sides of the desired polygon are known.

To measure four sided polygons, the operator drives the scanner **10** using the joystick **157'** such that the transducer **134** is at the corner of the polygon opposite the local origin, and presses a button on the screen indicating that the scanner is at the third reference point. Each of the three axis positions is recorded. The information stored is sufficient to indicate two possible polygons. The shape used will be the polygon with an interior angle greater than 180 degrees.

If the joystick **157'** is used during the teach-and-learn process, the joystick **157'** is connected to the scanner end of an umbilical cable **26**. The umbilical cable **26** connects the NDI probes **134** to the data acquisition and analysis system **22** and a servo amplifier chassis. The umbilical cable **26** assembly includes motor cables, encoder cable, joystick **157'** cable, two RF ultrasonic cables, two RF eddy current cables, couplant delivery tubing, and a flexible fully zippered umbilical cable **26** outer jacket. The jacket II is made from a material that will not scratch or otherwise damage the surface under inspection.

In addition to the scan control board **162**, the hardware subsystem **152** also includes an ultrasonic processor board **164**, an eddy current processor board **166**, and a video board. Board consolidation may be employed to reduce the number of boards used.

The ultrasonic board **164** is a multi-function board that includes an analog to digital (A/D) converter, a RF board, a video rectification board, a pulser receiver, a multiplexed ultrasonic receiver, digital amplitude correction (DAC), hardware gates, data compression, capabilities, video detection and run length encoding.

The analog to digital (A/D) portion of the ultrasonic board **164** operates at a user defined rate. In one embodiment, the rate may range between 1 and 100 MSPS, inclusive. The A/D conversion rate is selectable in distinct steps between 1 and 100 for convenience. For instance the rate may be selected in graduated steps, e.g., 5, 10, 15 SPS, etc. The A/D board also includes a sample memory divided between the two channels. In one embodiment, the A/D board includes an 8 Kb memory divided between the two channels.

The RF board processes and displays RF signals, including full wave rectified, positive half wave rectified and negative half wave rectified signals. The RF rectification portion of the ultrasonic board **164** accepts input from an external RF source or other sources having a voltage within the range of ±0.5 V. The data acquisition window for each channel is synchronized to the initial pulse or interface signal. The start point may be delayed up to 3 msec from the synchornization point.

The pulser receiver is a two channel device that generates and receives pulses from the ultrasonic transducer **134**. The channels may be operated simultaneously or multiplex. The pulser receiver supports a pulse-echo, pitch-catch, or through transmission modes of operation for each channel. Each pulser, channel, contains a square wave and a spike pulser. The operator selects the pulser type to be used on a given channel.

The square wave pulser uses a digitally programmable negative going square wave pulser. In one embodiment, the square pulser provides pulse voltage over a range of 50 to 400 V with rise less than or equal to 14 nanoseconds and a fall time of 60 nsec. Rise and fall times are measured at 10% and 90% amplitude points into a 100 ohm resistive load. The operator selects the pulse width over a range of 80 nsecs to 1 μsec in 20 nsec steps is provided. The operator also selects pulser damping settings in four distinct steps over the range of 50 to 400 ohms, inclusive. The spike pulser uses a digitally programmable spike pulser. In one embodiment, the spike pulser provides pulse voltages over a range of 50 to 400 V.

The multiplexed ultrasonic receiver receives and processes input signals. In one embodiment, the receiver has a frequency response of 0.5 to 30 MHz at −6 dB and 40 dB gain. The receiver provides 0 to 98 dB of gain in increments of 0.5 dB (−40 dB to +58 dB). Maximum error per 10 dB increment is measured at less than or equal to ±1.5 dB with a total error over the entire range measured at less than or equal to ±2.0 dB.

The receiver contains high pass and low pass filters. The filters may be used separately or in combination to produce a specific band pass filter. The receiver includes sufficient sensitivity and noise level capabilities. In one embodiment, receiver sensitivity is measured with a 200 μV peak to peak input signal and produces a corresponding full scale screen signal with a signal-to-noise ratio of 3 dB, when operated, for example, at 10 MHz low pass filter mode. The noise level does not exceed 40% grass level on screen at maximum gain.

Each receiver channel includes a DAC. The DAC is active over the entire acquisition time with each channel being independently controllable. The DAC utilizes up to 16 operator selectable segments with each segment being adjustable in width and slope. The operator through the software graphical interface selects the appropriate points for establishing the DAC curve. Each point is independent and can provide a positive or negative gain within the range of −20 dB to +58 dB. Overall DAC range is 38 dB within the overall receiver gain range. The maximum slew rate per segment is 24 dB per μsec.

The ultrasonic board **164** also contains both hardware and software gates, as discussed above. The ultrasonic board **164** includes four software flaw gates, two hardware flaw gates, one interface gate and one back-tracking gate per channel. The operator sets the delay and duration of the gates. The display is provided in both real time and metal path time.

With respect to the hardware gates, the ultrasonic board **164** includes one interface gate per channel and two dedicated flaw gates per channel. The operator may independently adjust the gate start position and width over the entire data acquisition range. The flaw gates acquire and store peak and time-of-flight data only. Operator selections are provided for acquiring the first signal amplitude in the gate, maximum peak signal in the gate, first signal amplitude above a selected threshold, and time-of-flight of the signal for any selected analysis mode.

The flaw gates are adjustable in position and width over the entire acquisition range. The settings for each flaw gate are digitally displayed in the gate calibration window. The display is also viewable by positioning of the system display cursor at a desired location on the display monitor. The flaw gate may be set to function over an operator selectable data acquisition delay. Gate delays are synchronized using either the initial pulse or the interface gate.

The ultrasonic board **164** also provides hardware for video detection. In one embodiment, the video board is a

VGA color board; however, other board types may be used. This hardware permits positive, negative, or full wave video signal or complete RF signals to be recorded and stored. Additionally, the hardware is associated with software that displays video signals while acquiring and storing RF waveforms.

The ultrasonic board **164** further includes hardware run length encoding for reducing data file size and increasing data acquisition rates. The data compression feature includes a threshold selection feature that provides noise suppression of displayed and acquired data, thus, also serving as a linear reject function. The data compression algorithm is discussed more fully below.

The ultrasonic board **164** includes software (discussed more fully below) and hardware that permit measurement of material thickness. In particular, the ultrasonic-board **164** components permit measurement of the thickness of aluminum down to 0.012 inches and reliably resolves a change in graphite/epoxy composite. In one embodiment, the ultrasonic board **164** resolves graphite/epoxy composite structures ranging in thickness from 1 ply to 120 plies.

The ultrasonic board **164** meets the horizontal and vertical linearity requirements stated herein when tested in accordance with paragraph 5.2 of ASTM E317-85 and method B defined in paragraph 5.3.3 of ASTM E317-85, both incorporated herein by reference.

The ultrasonic board **164** meets the near surface and depth resolution requirements described herein when tested in accordance with the following procedure. In both tests, the reject is in the "off" position, and aluminum ASTM blocks are used.

The ultrasonic board **164** satisfies the resolution requirements of Paragraph 5.4 of ASTM E317-85, incorporated herein by reference, when tested in accordance with the method outlined in this paragraph using the frequencies, transducer **134** diameters, ASTM hole sizes and hole depths stated in Table 1 below. The 80% and 20 specified in Paragraph 5.4 shall be changed to 1000% and 10%, respectively. The indication from the flat bottom hole is clearly distinguishable from the initial pulse. The peak amplitude of this signal meets the peak to valley ratio stated in Table 1 when compared to the initial pulse trailing edge valley amplitude. With the transducer **134** positioned away from the flat bottom hole, the resulting baseline signal amplitude, in the area of the hole signal, is such that the stated peak to valley ratio is also met when compared to the hole signal amplitude.

TABLE 1

RESOLUTION

Frequency (MHz)	Transducer Diameter (inches)	ASTM Hole Size (aluminum block)	Hole Depth Below Surface (inches)	Peak-Valley Ratio	Display Mode
2.25	½	5	0.100	10–1	Full wave
5.0	¼	5	0.050	10–1	Full wave
10.0	¼	2	0.050	10–1	Full wave
10.0	¼	1	0.050	7–1	Any mode

In addition to the sensitivity requirement set forth herein, the ultrasonic board **164** satisfies the sensitivity requirement of Paragraph 5.5 of ASTM E317-85, incorporated herein by reference, with the following modifications: (1) the reference level indications are 100% of full scale instead of 60%, (2) the required signal to noise ratio are as specified in Table 2 below, and (3) the reject is in the "off" position.

TABLE 2

SENSITIVITY

Frequency (MHz)	Transducer Diameter (inches)	ASTM Block Number (aluminum)	Signal-Noise-Ratio	Gain Limit (% of maximum positive gain)
2.25	½	2-0300	5–1	75
5.0	5/16	1-0300	5–1	75
10.0	¼	1-0300	10–1	80

The ultrasonic board **164** also satisfies the gain accuracy requirements specified herein when tested in accordance with Paragraph 6.22.2 of AWS D1.1-94 and Paragraph 5.6 of ASTM E317-85, both incorporated herein by reference.

Turning now to the eddy current board **166**, the eddy current board **166** of the data acquisition and analysis system **22** uses a dual frequency dual channel card for acquisition of eddy current data. In one embodiment, the eddy current board **166** has a frequency range of 50 Hz to 4 MHz. The eddy current board **166** supports absolute, differential and driver pickup style eddy current probes.

The eddy current board **166** includes an A/D converter. In one embodiment, the A/D converter of the eddy current board **166** operates at a rate of 2,000 SPS for single channel operation and 1,000 SPS for multiple channel operation. The converter provides **12** bit resolution.

The eddy current board **166** also includes a driver and receiver. The driver permits adjustment of the drive voltage applied to the test coils. The exact voltage applied to the coils is a function of their nominal impedance and the excitation frequency. The operator selects the specific drive integer applied. The receiver adjusts the gain setting. In one embodiment, the gain is adjusted from 0 to 48 dB in controlled increments.

The eddy current board **166** is associated with software (discussed more fully below) and hardware that provide a display of a clear indication (a vertical deflection of the displayed screen, with an operator selectable signal to noise ratio of the vertical component). In one embodiment the vertical deflection ranges between 30–40% of the displayed screen. The accuracy of the display is measured using Air Force General Purpose Eddy Current Standard, Part No. 7947479-10 or AMS 4928, both incorporated herein by reference. These standards may be used to measure the performance for aluminum and titanium materials. It will be appreciated that other materials may be selected, and the test protocol modified accordingly.

In a faying surface, the eddy current board **166** provides a display of a clear indication (a vertical deflection of the displayed screen, with an operator selectable signal to noise ratio). The signal to noise ratio is determined by comparing average peak to peak signals over a defect free fastener hole to repeated scans over one with a defect present to obtain the average signal amplitude and the maximum width of the signal signature traces to obtain the noise amplitude. The inspection is conducted with the fasteners installed using a reflection or driver pickup type probe. Steel fasteners are highly susceptible to detection.

The eddy current board **166** uses dual frequencies to reduce unwanted signals from gaps between two 0.040 inch thick aluminum sheets. The eddy current board **166** produces a minimum of 20% of the displayed screen for a wall loss, of 10% originating on the rear side of the second layer. The wall loss signal to gap signal ratio is greater than or equal to four. The gap variance range is 0.000 to 0.025

inches. The ratio of the electrical noise, with the probe stationary, is 10 to 1 compared to the 10% wall loss signal. The eddy current board **166** indicates a faying surface 10% wall thickness loss over a one inch diameter area in an aluminum plate with thicknesses up to 0.120 inches.

The data acquisition and analysis system **22** also includes an external signal interface module. The external interface module accepts input signals from external NDI equipment for acquisition, display and storage. The input is through the ultrasonic board **164** via the A/D converter. The sample rate can be varied as required.

In one embodiment, the module converts external signals within a ±10 V amplitude range to a compatible range of ±0.5 V for input to the ultrasonic board **164** A/D converter. The converted signals are displayed from 0–100% of full screen height through the use of the system receiver gain, and provides a vertical linearity within 5% of full scale. The input impedance is also converted to obtain compatibility with the A/D converter. The input connector is of the standard BNC type.

Turning now to a discussion of the data acquisition and analysis system **22** software subsystem **150**, the software subsystem **150** includes various software files that control the operation of the scanner **10**. The software subsystem **150** stores processor setup, operating and image display parameters on a selected file for easy reference. In essence, the software subsystem **150** files store the operating parameters for controlling scanner **10** functions. In operation, the files permit various types of information to be retrieved and evaluated regarding the integrity of the surface under inspection. This information includes ultrasonic, eddy current, as well as other NDI generated data. Upon loading an existing file, the operator may repeat any previous scan or rapidly alter the system configuration to perform a new scan.

The software subsystem **150** files include data correction functions that correct for offsets in adjacent data strokes due to mechanical hysteresis. The operator inputs an integer value and the software shifts every other stroke by this value.

One version of the software subsystem **150** files is UNIX based, and is displayed on the display screen of the host computer **154** using an X-Windows™/Motif based format. It will be appreciated that other software formats may be used. The UNIX based format provides the operator the ability to adjust the size of any display window, adjust the number of open windows, and adjust the layering of the windows as desired. As discussed above, user interface is achieved using the keyboard **160** or a pointing device **157** such as a mouse. As previously discussed, the operator executes commands through the use of pull-down and/or tear-off menus.

The software subsystem **150** permits transferring data files via modem or LAN to another computer or device for post analysis or review. To further facilitate review of the stored data or processed information, the software subsystem **150** includes files for converting data to commonly used data formats, including but limited to, TIFF format files. If a TIFF converter is used, the files may be reviewed and analyzed on a separate computer. In one embodiment, National Institute of Health image analysis software, version 1.52 or equivalent may be used to analyze the data.

With respect to ultrasonic, time-of-flight, amplitude and raw inspection data, the data may be formatted into separate TIFF files. With respect to eddy current and other NDI instrument files, the raw data and image files may be formatted as separate TIFF files. The TIFF files may be converted to other formats, for example MS-DOS or PC compatible, without the loss of data or a reduction in the data's quality.

Additionally, the files include real-time multi-tasking with a graphical user interface. The multi-tasking capabilities permit an operator to analyze a file, print images from that file, and acquire data simultaneously. The files also provide for computer **154** realignment of possible skewed data from scanner mechanical hysteresis resulting from bi-directional scanning.

The following discussion describes the hardware subsystem **152** and the software subsystem **150** capabilities in the calibration mode. With regard to ultrasonic calibration, the data acquisition and analysis system **22** provides the operator with control over scanner **10** related functions, including movement, position, and scan parameters. The operator also has control over the scanner **10** settings. Functions controlled in the calibration mode include gate and channel selection, data acquisition type selection, signal processing selection, data compression, distance amplitude correction (DAC), pulser preamp adjustment, gate adjust, and A-scope.

With regard to gate and channel selection, the operator chooses which channel and gates to be utilized during data processing. As previously discussed, the ultrasonic board **164** includes two channels. Each channel has four software flaw gates, two hardware flaw gates, one interface gate, and one back-tracking gate.

Since the operator has control over the type of data selected for processing, the operator can configure the system to record full RF, video or peak and time of flight data. The operator may adjust the A/D rate to discrete values as, discussed above, between one and 100 MSPS, inclusive.

With regard to signal processing selection, the operator selects the signal processing method used. The operator may also choose to activate the data compression algorithm. The data compression algorithm is based on amplitude and duration. The RF data must be below the defined amplitude for the number of defined data points for compression to occur. This ensures that the complete decay of actual signals will be recorded. RF values of zero are substituted for the data points when the data compression occurs. The result is a significant reduction of the data file size.

Additionally, the operator has control over the distance amplitude correction (DAC) function. This function allows the operator to apply a correction that adjusts the gain applied to the data as a function of time and to normalize the amplitude response of signals over time. In one embodiment, the data acquisition and analysis system **22** provides 38 dB of dynamic range for the DAC gain. This gain is limited so that the total effective gain is within the 0 to 100 dB of system gain.

With regard to pulser preamp adjustment, the operator first selects either the square wave pulser or the spike pulser. Secondly, the operator selects the voltage applied by the pulser and the width of the square wave pulser. Next, the operator selects the damping, filtering and gain parameters to be applied.

The operator also configures the screen display **158** to provide a standard A-scan format of the type normally displayed on manual CRT ultrasonic instruments. The display **158** provides a plot of percentage full screen height versus time. The operator uses this display to perform initial system calibration. In this mode, the operator has control over the selection of the ultrasonic parameters, including delay and duration of gates, A/D rate, gain, pulse voltage and duration, and transducer **134** mode. The operator interactively adjusts these parameters until the proper calibration is achieved.

The operator also adjusts a variety of display features from the calibration menu, including rotation, amplitude

scale, cursor width, vertical to horizontal ratio, and vertical strip chart time scale. These features may be adjusted prior to or after data is acquired. Additionally, the operator performs multifrequency mixing to suppress undesired signals by selecting the signal to suppress and performing the mix in the calibration mode.

The eddy current board 166 permits the setting of a hardware null and a selectable software null to define a data display/computer reference point. The operator sets the hardware null in the calibration mode by performing a hardware balance. The operator adjusts the eddy current board 166 settings so that the probe operating point is at the center of the total impedance dynamic range.

The operator also adjusts the center reference point during or after data acquisition. The cursor location is defined as the null point. The scanner 10 display features are based on this null point, and C-scans are computed based upon how the given data point differs from this null point.

The operator also has control over other eddy current calibration features. In the eddy current calibration mode, the data acquisition and analysis system 22 acts as a standard impedance plane eddy current instrument. The operator adjusts eddy current related functions from a calibration menu selectable from the pull-down menu. Through the calibration menu the operator adjusts the operating frequency, probe type, gain and coil voltage. In one embodiment, the operating frequency ranges between 50 Hz and 4 MHz, and the probe type is an absolute, differential or driver/pickup. The gain is set between 0 and 48 dB, inclusive, and the coil voltage ranges between 1 and 16 V, inclusive.

In the eddy current calibration mode, the operator also adjusts the scan control features. The standard method of inspection is to perform boustrophedonic (bi-directional or meander) scans. The operator defines a scan pattern by specifying the stroke length step and index range, along with the sampling grid spacing between pulses. The start and stop point for a scan may be any value. This allows the origin for the scan to correspond to some reference datum point on the component being inspected.

The data acquisition and analysis system 22 includes a variety of analysis features, each of which will be discussed below. The data display capabilities of the data acquisition and analysis system 22 permits rapid review of the data for possible reportable indications. Consequently, the operator can concentrate on performing a detailed review of these indications. The data is displayed in either metric or English units of measure.

The data acquisition and analysis system 22 permits adjusting the content and scale of the analysis screen display. The operator independently adjusts the area of the display used for each of the four major analyses screen elements: legend, C-scan, B-scan and A-scan. The legend displays system configuration parameters such as file name, scan parameters, ultrasonic parameters.

The C-scan display is a plan top view of data within a specified C-gate. The operator chooses what slice(s) to display by adjusting the C-gate or by selecting a different C-gate. The operator may perform this function at any time without repeating the scan. Additionally, the operator displays the parameter of interest using a variety of colors selectable from the palette. The operator may alter the color palette as well as add values associated with the color(s) selected.

The C-scan display presents the C-scan as either a peak, time-of-flight, decibel, threshold peak, depth, or polarity display. When displayed as a peak, the amplitude C-scan color codes and displays the maximum rectified amplitude in the C-gate for each waveform. In the time-of-flight mode, the C-scan color codes and displays the time-of-flight for a signal in the C-gate for each waveform. The time-of-flight is selected as either the time to the first threshold crossing or the maximum signals within the C-gate. If multiple and equal maxima are encountered, the first maximum is used. The data can be expressed in terms of time, depth, and metal path or in any other appropriate manner.

With regard to time-of-flight, this function measures the thickness of a surface under inspection as described above for the ultrasonic board 164. Two separate types of results are provided. The first provides the location and value of the maximum and minimum wall thickness. The second provides the percentage of area with a thickness reading greater than and less than a user specified minimum thickness threshold.

Additionally, when the C-scan is presented as a decibel scale, data is displayed as amplitude values relative to an operator defined FSH percentage. As a threshold peak, the C-scan is the same as the peak C-scan except any data point with a value below an operator specified threshold is plotted as background color. Using the depth type display, the C-scan is based on the time-of-flight data but uses inches instead of microseconds for the color map. The velocity of the sound value and the wedge delay are used to calculate the depth. The maximum and minimum depth values correspond to the start and stop of the C-gate. Finally, as a polarity display, the color map provides an amplitude map with the colors differentiating between positive and negative going signals. The polarity C-scan type is effective if RF data recording was selected.

The operator may define the upper and lower limit for the color scale used for any given C-scan type. Any value above or below the selected limits is assigned a specified color value. The color scale used with the C-scan will be a linear distribution between the defined upper and lower limits.

The operator may select from a variety of existing color pallets for use with the C- and B-scans. The operator may also modify an existing pallet to generate a new pallet.

Additionally, the data acquisition and analysis system 22 includes software associated with the ultrasonic board 164 for analyzing synthetic aperture focusing to correct B- and C-scan displays for beam profile parameters, and C-scan RF signal leading edge polarity (at zero crossing) display of either a maximum or minimum, above a selectable threshold, signal in a specified A-scan gate or first signal, above a selected threshold, in an A-scan gate. The data acquisition and analysis system 22 also includes software associated with the ultrasonic analyzer 164 for performing ratio analysis of selected peak amplitude signals or integrated rectified signals from two separate independent gates to determine relative disbond/good bond signal decay rates.

The data acquisition and analysis system 22 includes zoom capabilities. The data acquisition and analysis system 22 uses a maximum of "n" compression algorithms to display images. This routine is used when the number of data points is larger than what can be shown on the screen area assigned to the image. The operator can zoom the C-scan image to display the acquired data points.

The data acquisition and analysis system 22 includes a scroll feature that permits an operator to view a C-scan having a size that exceeds the screen display limits. For such a C-scan, only a portion of the C-scan is displayed at a time. The scroll feature allows the operator to pan across the entire data display. The data acquisition and analysis system 22 also permits the operator to swap the display axis of the C-scan data.

The data acquisition and analysis system 22 also includes software files for performing statistical analyses on an operator selected portion of the C-scan. The statistics calculations performed include time-of-flight and amplitude based analyses.

Amplitude statistics examine amplitude measurements. Again, two types of results are provided. The first provides the location and value of the maximum and minimum amplitude values above an operator specified threshold. The second provides the percentage of area with an amplitude reading greater than and less than an operator specified value.

Further, the data acquisition and analysis system 22 includes an interleave function. This function allows the operator to combine data obtained from separate transducers 134 into a single image. Specifically, this function merges the peak and time-of-flight data from channels 1 and 2 of the same data file.

Turning now to B-scans, a B-scan is a graphic presentation of a section view. The B-scan display uses the same color palette as the amplitude C-scan to represent the amplitude of the waveform for each discrete data point recorded through time.

The data acquisition and analysis system 22 includes a cursor for moving through the B-scan. The operator uses the cursor to select a waveform (A-Scan). The wave form is displayed below the B-scan. In addition, the operator uses the cursor to select a specific data point to find the peak within the active C-gate. The data acquisition and analysis system 22 graphically displays the incident skew angles in the B-scan.

The data acquisition and analysis system 22 permits the operator to display the B-scan using colors selected from the color palette or using various shades of gray, also selected from the color palette. The operator performs time-of-flight tip defraction analysis while using a polarized gray scale in the B-scan.

The data acquisition and analysis system 22 B-scan display includes a zoom function, and uses a maximum on "n" compression algorithms to display images. This routine is used when the number of data points is larger than what can be shown on the screen area assigned to the image. The operator zooms the B-scan image to show the acquired data points.

The data acquisition and analysis system 22 includes a scroll feature that permits the operator to view a B-scan having a size that exceeds the screen display limits. For such a B-scan, only a portion of the B-scan is displayed at a time. The scroll feature allows the operator to pan across the entire data display. Additionally, the operator may adjust the B-scan for curvature correction. This function adjusts the depth, metal path, and surface position to correct for the effect of a curved surface.

For B-scan data, the data acquisition and analysis system 22 includes timebase time-of-flight and metal path selection functions. These functions let the operator display the scan in terms of time or distance. The display screen shows the chosen units. With regard to the metal path, the zero depth-position is defined by the wedge delay.

The operator performs measurements on signals on the B-scan using a calibrated measurement function. The system uses two measurement cursors. The first is the reference line, and the second is the measurement line. The calibrated measurement function can be used in two ways. The first is to perform a delta measurement. For this application, the operator places a dotted cursor at one position and a solid cursor at a second position. The distance between the two is displayed. The second is to perform a calculated depth measurement. This is used to define depth measurements based on operator selected signals. The operator selects any point within the B-scan and defines the actual depth of this point. This function is generally used when normal measurement values are not accurate.

The data acquisition and analysis system 22 also includes a weld overlay function. This function displays a pictorial representation of the weld on the B-scan display, and helps identify reflectors generated due to weld geometry. Additionally, the data acquisition and analysis system 22 includes software for performing Fast Fourier Transform (FFT) analysis on selected waveforms in the B-scan (FFT may also be used for C-scan analysis).

The data acquisition and analysis system 22 also uses synthetic aperture focusing techniques (SAFT) to simulate the focal properties of a large-aperture, focused transducer 134 using data acquired with a small-aperture transducer 134 that has been scanned over a large area. Line SAFT, a two-dimensional version of SAFT, is performed on-line and in the field. Line SAFT generally requires significantly fewer calculations than three-dimensional SAFT.

The data acquisition and analysis system 22 includes software and hardware for displaying B'-scans. The display features discussed for the B-scan are included as elements of the B'-scan display.

With regard to A-scans, an A-scan is a graphic representation of the recorded RF waveform. The A-scan is displayed in either video or RF mode. The data acquisition and analysis system 22 via the ultrasonic board 164 supports RF, full wave rectified and positive and negative half wave rectified data. To display positive and negative half wave rectified data, the data must be acquired in the desired half wave mode.

The data acquisition and analysis system 22 includes a variety of eddy current analysis features, each of which shall now be discussed. The data display capabilities of the data acquisition and analysis system 22 are designed to allow rapid review of the data for possible reportable indications. The operator, thus, can concentrate on performing a detailed review of these indications, and performing an analysis of the data at any time on any file, including during data acquisition. The data acquisition and analysis system 22 displays the data in either metric or English units.

For example, the eddy current analyzer 166 includes software that permits simultaneous presentations of impedance plane, sweep and C-scans so that the operator can monitor the scan images and signal data as they are generated. The analysis includes C-scans based on impedance magnitude, impedance phase, horizontal impedance component, and vertical impedance component. The impedance phase C-scan is calibrated in degrees and the other C-scans are based on percent of full dynamic range. The analysis provides for C-scans based on the spatial derivative of above C-scans to characterize signals representing a high rate of change in phase and magnitude.

The analysis also provides for impedance plane displays and corresponding sweep displays of the vertical and horizontal impedance components. The data acquisition and analysis system 22 stores the digitized impedance data along with positional information. This method of data storage permits the generation of the type of C-scan displays discussed below along with the creation of synthesized strip charts and impedance plane displays. The screen is configured for combinations of simultaneous data displays, including up to two different C-scans and an impedance plane display. The data acquisition and analysis system 22 pro-

vides the ability to adjust the content and scale of the analysis screen display.

Since the raw data is stored, post inspection software parameters such as, but not limited to, phase, vertical/horizontal scaling may be varied and the corresponding C-scans, sweeps and impedance planes recomputed. An analysis is provided for variable vertical horizontal amplitude ratio scaling. Dual frequency mixing is displayed in the impedance plane format. The operator adjusts the area of the display used for legend and C-scan information. The legend displays system configuration parameters such as file name, scan parameters, and eddy current parameters.

As with ultrasonic data, the C-scan is a top plan view of the data. For each channel of acquired data, the operator displays a choice of C-scan types, discussed below, for each channel. The parameter of interest is displayed using color (s) selected from the color palette. The operator may alter the color palette used as well as the values, if any, associated with each color.

The type of C-scan displays that may be generated include horizontal amplitude, vertical amplitude, magnitude, phase, and first spatial derivative. For horizontal amplitude, the horizontal component of the impedance plane data is plotted relative to the operator defined center value. The data displayed is plotted in terms of eddy current units (ECU).

The eddy current board 166 used with the system has a total digital dynamic range of ±4K. One data point of that dynamic range equals one ECU. Thus, the ECU provides a measure of the amplitude of the signal. As to the vertical amplitude, the vertical component of the impedance plane data is plotted relative to the operator defined center value. The data is plotted in terms of ECUs. The magnitude display, is a vector sum of the horizontal and vertical displays. The magnitude of the impedance plane data is plotted relative to the operator defined center value, and the data is plotted in terms of ECUs.

The phase display is plotted as the phase angle of the impedance plane relative to an operator defined center. The data is plotted in terms of degrees. The operator specifies a magnitude threshold for use with the phase C-scan. The magnitude of any given data point must equal or exceed the threshold for the phase C-scan to display any color other than the "under" color. Finally, the first spatial derivative of any of the above four C-scans can be selected. The operator selects the number of data points over which the derivative is calculated.

In displaying the scans, the operator defines the upper and lower limits for the color scale used for any given C-scan type. Any value above or below the defined limits is assigned a specific color value. The color scale used with the C-scan will be a linear distribution between the defined upper and lower limits. The operator selects the desired color(s) using the color pallet. The operator may also modify an existing pallet to generate a new pallet.

The data acquisition and analysis system 22 includes a zoom function for displaying eddy current data. The data acquisition and analysis system 22 uses a maximum of "n" compression algorithms to display images. This routine is used when the number of data points is larger than what can be shown on the screen area assigned to the image. The operator zooms the C-scan image to show the acquired data points.

Another feature of the eddy current board 166 is a scroll function. The scroll function permits the viewing a C-scan having a size that exceeds the screen display limits. For such a C-scan, only a portion of the C-scan is displayed at a time. The scroll feature allows the operator to pan across the entire data display. The operator may also swap the display axis of the C-scan data using the swap axis function.

The eddy current analyzer 166 includes a lissajous display. Complex impedance data for a specified channel is displayed using the lissajous display. The cursor location and width define the data displayed. The operator, thus, can display the actual data value for any C-scan type and channel.

Additionally, the eddy current analyzer 166 includes a vertical/horizontal (V/H) ratio function for applying separate scaling factors to the horizontal and vertical components of the signal. This is accomplished using the V/H parameter. This variable is a post acquisition item. The V/H parameter effects strip charts, lissajous displays and C-scans, and is useful in increasing the phase separation between lift-off signals and small near surface flaws.

The eddy current analyzer 166 also includes high and low pass filters for treating the eddy current data. The filters are applied to the acquired data. Another feature of the eddy current analyzer 166 is a depth indication merge (DIM) file. The DIM file combines data obtained from separate channels (transducers) and/or files inspecting the same volume at different skew and/or inspection angles. The results provide C- and B-scans of the data where the colors indicate which channel or combination of channels have an indication above a specified threshold.

The data acquisition and analysis system 22 provides C-scan measurements of defect parameters, including, but not limited to, width, length, area, minimum/maximum defect spacing, defect to non-defect area percentage over a defined area, mean, standard deviation, X-Y location on the part being inspected. Additionally, the data acquisition and analysis system 22 generates B-scan measurement of parameters, including, but not limited to, defect depth, length/width, part thickness, and percent remaining part thickness.

The data acquisition and analysis system 22 includes a C-scan histogram function that lets the operator select an area of the C-scan with a "rubber-band box". The data in the selected area is compiled and displayed such that the number of occurrences of data in each data range is indicated in the form of a histogram chart.

Finally, the scanner 10 includes a portable scanner 168. The portable scanner 168 is compatible with the data acquisition and analysis system 22 of the scanner 10. Like the automated scanner 10, the portable scanner 168 is capable of ultrasonic and eddy current inspections. The X- and Y-axes of the portable scanner 168 may be locked to facilitate rectilinear scanning. Additionally, as with the automatic scanner 10, the portable scanner 168 is adapted for use on curved surfaces, and is capable of being vacuum loaded to the surface to be inspected.

It will be appreciated that the scanner 10 has been described in accordance with the illustration shown in FIGS. 1–10, and may include operational and functional characteristics other than those described.

Installation

To facilitate installation of the inspection system 10 by a single operator, each axis 28, 30 and 32 may be loaded independently. Further, each axis tractor 82, 84 and 86 may be loaded independently of its respective track assembly 28, 30, and 32. The following procedure may be used to install the scanner 10. For illustration purposes, the selected inspection area for the stated procedure is four feet along the X-axes 28, 30 and six feet in the Y-axis 32 direction. The operator installs the master X-axis 28 on the surface to be

inspected. The master X-axis 28 tractor assembly 82 is installed on the X-axis vacuum track 28 assembly. The operation then installs the slave X-axis track assembly 30. This installation is followed by the installation of the slave X-axis tractor assembly 84 onto the slave X-axis track assembly 30. The operator next secures the Y-axis track assembly 32 to the master and slave X-axis tractor assembly 82, 84 using quick disconnect coupling. The Y-axis tractor 86 and thruster assembly 18 are installed on the Y-axis track assembly 32. Next, the operator connects the umbilical cable assembly 26 to the scanner 10. The scanner 10 is also tethered to an external surface to prevent damage in the event the scanner 10 becomes inadvertently detached from the inspection surface.

Operation

After scanner 10 installation is complete, the operator drives the NDI probe(s) 134 to the zero or starting position using the handheld joystick 157' and zeros the encoders by pressing a single control. If a scan plan has not been taught, the operator accomplishes teaching the inspection area as described herein. If a scan plan has already been taught, the operator inputs the scan plan via an applicable file name.

If performing an ultrasonic inspection, the system prompts the operator to enable the couplant supply system 24 prior to scanning and to disable the couplant system 24 at the termination of the scanning sequence.

Upon operator initiation of a scan cycle, the scan control subsystem 20 drives the scanner 10 back to the zero position (if not already at this position) and commences the scanning operation upon operator command. The operator selects the format for displaying the data. For instance, the operator selects real-time amplitude based or time-of-flight based C-scans or selects to display the RF waveform data. A C-scan is generated for each gate utilized per channel, though only one C-scan at a time is displayed.

The data acquired at each grid point is displayed (a C-scan and an A-scan) in near real-time. This provides direct visual feedback of both scanner location and direction. In addition, the quality of the data may be verified. Additionally, the scanner 10 is monitored for slippage by using a close loop tolerance technique. Excess slippage or drift causes the system to automatically terminate the scan and provide an error message.

As discussed above, the movement of the scanner 10 assembly is controlled by an external three-axis scan control subsystem 20. The scan control subsystem 20 manipulates the NDI probes 134 using the preprogrammed rectilinear scan pattern. This scan pattern is referenced to the operator defined global coordinate system. The manipulation of the NDI probe 134 along the global axes is accomplished by coordinating the movement of the master X-axis tractor 82, slave X-axis tractor 84 and the Y-axis tractor 86 along their respective track systems 28, 30, and 32.

In controlling the scanner 10, the operator may enter a pause command, temporarily suspending the scanner 10 operation, at any time during the scan cycle. Additionally, the scan cycle may be terminated under three conditions: normal completion, operator termination and system termination. A normal completion occurs when the scanner 10 has completed the entire specified scan pattern. The operator may terminate the scan at any time, and the data acquired analyzed. However, when a scan is terminated before completion, the appropriate software subsystem 150 file is updated to provide a message that the scan was only partially completed. Finally, the system will terminate the scan upon detection of fault conditions, including scanner 10 slip, drift, or excessive velocity.

With respect to ultrasonic data acquisition, the data acquisition and analysis system 22 utilizes the scan pattern, ultrasonic calibration and eddy current calibration defined by the appropriate software file(s). During the ultrasonic data acquisition process, the scan control subsystem 20 moves the NDI probes 134 in the prearranged pattern as defined by the operator. At the specified coordinate positions (grid), the scan control subsystem 20 generates sync pulses. This causes the pulser to pulse and the ultrasonic board 164 to receive data.

This pulse on position technique results in the generation of ultrasonic waveforms at specified grid points. The data acquisition and analysis system 22 reads the full ultrasonic waveform, the video data, or the peak and time of flight information for each grid point. Additionally, the operator acquires multiple waveforms at each grid location as well as acquiring eddy current data simultaneously, multiplexed, with ultrasonic scans. Converted signals from other NDI equipment are collected in the same pulse on position manor.

Eddy current data acquisition occurs similarly. This activity is done simultaneously with ultrasonic data acquisition or separately, as the eddy current board 166 is continuously operating. When a sync pulse is received, the horizontal and vertical components of the impedance data for each active frequency and probe are recorded. The acquired data is stored in memory as a background task during data acquisition. This prevents loss of data due to AC power interruption.

There are a variety of configurations that may be employed to fabricate the scanner 10. Thus, the disclosed embodiment is given to illustrate the invention. However, it is not intended to limit the scope and spirit of the invention. Therefore, the invention should be limited only by the appended claims.

We claim:

1. A surface scanner comprising:

a first flexible track assembly supporting a first motorized tractor assembly;

a second flexible track assembly supporting a second motorized tractor assembly;

a third track assembly supported by the first track assembly and the second flexible track assembly;

a third motorized tractor assembly supported by the third track assembly;

a thruster assembly supported by the third motorized tractor assembly;

at least one inspection probe supported by the thruster assembly;

scan control means for moving said at least one inspection probe over a surface to be inspected; and

data acquisition and analysis means for acquiring data from said inspection probe related to a scan of at least a portion of said surface, and analyzing said data for defects in said surface.

2. The surface scanner as defined in claim 1, wherein the first flexible track assembly and the second flexible track assembly include a plurality of interconnecting track plates.

3. The surface scanner as defined in claim 2, wherein the track plates are flexible members, said track plates do not plastically deform upon bending and twisting.

4. The surface scanner as defined in claim 3, wherein the interconnecting track plates are fabricated of spring steel.

5. The surface scanner as defined in claim 3, wherein the track plates are adjusted to mate with complex surface configurations.

6. The surface scanner as defined in claim 5, wherein the track plates are adjusted to mate with aircraft surfaces.

7. The surface scanner as defined in claim 1, wherein the first flexible track assembly and the second flexible track assembly support a plurality of vacuum cup assemblies coupled to a vacuum source.

8. The surface scanner as defined in claim 7, wherein the scanner includes a warning for alerting an operator of a loss of vacuum pressure.

9. The surface scanner as defined in claim 8, wherein each vacuum cup forming the plurality of vacuum cup assemblies includes a mounting hinge for adjusting the angular position of the vacuum cup assembly.

10. The surface scanner as defined in claim 1, wherein the first flexible track assembly and the second flexible track assembly support end of travel stops at each end thereof.

11. The surface scanner as defined in claim 1, wherein the first flexible track assembly and the second flexible track assembly each supports gear racks.

12. The surface scanner as defined in claim 11, wherein each gear rack receives a mating gear supported by the respective tractor assembly.

13. The surface scanner as defined in claim 12, wherein the mating gear is a pinion gear.

14. The surface scanner as defined in claim 13, wherein the pinion gear is motor driven.

15. The surface scanner as defined in claim 1, wherein the first tractor assembly and the second tractor assembly support a plurality of guide rollers for engaging, respectively, the first flexible track assembly and the second flexible track assembly.

16. The surface scanner as defined in claim 1, wherein the first tractor assembly and the second tractor assembly support at least one clamping handle for respectively coupling the first tractor assembly and the second tractor assembly to the first flexible track assembly and the second flexible track assembly.

17. The surface scanner as defined in claim 1, wherein the first tractor assembly and the second tractor assembly each supports an optical encoder.

18. The surface scanner as defined in claim 1, wherein the second tractor assembly includes a position adjustment mechanism for permitting movement along three axes of freedom relative to the third track assembly.

19. The surface scanner as defined in claim 1, wherein the third track assembly includes one track plate coupled to a rigid strut.

20. The surface scanner as defined in claim 19, wherein the third track assembly is fabricated with a spring steel track plate and aluminum strut.

21. The surface scanner as defined in claim 1, wherein the third track assembly supports end of travel stops at each end thereof.

22. The surface scanner as defined in claim 1, wherein the third track assembly supports a gear rack.

23. The surface scanner as defined in claim 22, wherein the gear rack receives a mating gear supported by the third tractor assembly.

24. The surface scanner as defined in claim 23, wherein the mating gear is a pinion gear.

25. The surface scanner as defined in claim 24, wherein the pinion gear is motor driven.

26. The surface scanner as defined in claim 1, wherein the third tractor assembly supports a plurality of guide rollers for engaging the third track assembly.

27. The surface scanner as defined in claim 1, wherein the third tractor assembly supports at least one clamping handle for coupling the third tractor assembly to the third track assembly.

28. The surface scanner as defined in claim 1, wherein the third tractor assembly supports an optical encoder.

29. The surface scanner as defined in claim 1, wherein the surface scanner is lightweight.

30. The surface scanner as defined in claim 1, wherein articulating joints couple the third track assembly to the first track assembly and the second track assembly.

31. The surface scanner as defined in claim 30, wherein the joints permit non-parallelism and twist of the first track assembly and second track assembly relative to one another.

32. The surface scanner as defined in claim 30, wherein the joints are quick connect and disconnect couplers.

33. The surface scanner as defined in claim 1, wherein the third track assembly supports a master mounting bracket for permitting movement along multiple axes of freedom.

34. The surface scanner as defined in claim 33, wherein the master mounting bracket includes an angle dial plate.

35. The surface scanner as defined in claim 34, wherein the master mounting bracket includes an indicator for marking the angular position of the angle dial plate.

36. The surface scanner as defined in claim 35, wherein the master mounting bracket includes a pivot mechanism for permitting a relative change in position of the third track assembly and the first track assembly.

37. The surface scanner as defined in claim 36, wherein the pivot mechanism includes an upper pivot block and a lower pivot block.

38. The surface scanner as defined in claim 1, wherein the scanner includes vacuum coupled fixturing for offsetting the first track assembly and the second track assembly from the edges of the surface to be inspected.

39. The surface scanner as defined in claim 1, wherein the third track assembly has a liner stroke of 6 feet.

40. The surface scanner as defined in claim 1, wherein the third tractor assembly supports a BNC connector array.

41. The surface scanner as defined in claim 1, wherein the third tractor assembly supports said thruster assembly for moving the scanner over the surface to be inspected.

42. The surface scanner as defined in claim 41, wherein the thruster assembly is supported by either the top or bottom surface of the third track assembly.

43. The surface scanner as defined in claim 42, wherein the thruster assembly includes a slide block for facilitating movement of the thruster assembly.

44. The surface scanner as defined in claim 1, wherein the third tractor assembly supports nondestructive inspection probes.

45. The surface scanner as defined in claim 44, wherein the third tractor assembly includes a gimbal for supporting one or more nondestructive inspection (NDI) probes.

46. The surface scanner as defined in claim 45, wherein the NDI probes include mechanical impedance, ultrasonic or eddy current NDI probes.

47. The surface scanner as defined in claim 45, wherein the inspection probes include a single transducer probe.

48. The surface scanner as defined in claim 45, wherein the inspection probes include an eddy current probe sled assembly.

49. The surface scanner as defined in claim 45, wherein the gimbal positively loads the inspection probes, keeping them in contact with the surface to be inspected.

50. The surface scanner as defined in claim 49, wherein the gimbal supports a gas spring for positively loading the inspection probes.

51. The surface scanner as defined in claim 50, wherein an interface block couples the gas spring to the gimbal.

52. The surface scanner as defined in claim 1, wherein the scanner further includes a plurality of inspection probes that

are NDI probes and said scanner includes a couplant delivery system for supplying couplant fluid to the NDI probes.

53. The surface scanner as defined in claim **52**, wherein the probes are ultrasonic probes and said couplant delivery system supplies couplant fluid to the ultrasonic NDI probes.

54. The surface scanner as defined in claim **52**, wherein the couplant delivery system includes a delivery pump for circulating the couplant fluid, a supply tank for retaining the couplant fluid, and tubing interconnecting the pump, the supply tank and the NDI probes.

55. The surface scanner as defined in claim **54**, wherein the couplant deliver system includes a filter for removing particulates from the couplant fluid.

56. The surface scanner as defined in claim **54**, wherein the couplant delivery system further includes couplant retrieval gutters.

57. The surface scanner as defined in claim **52**, wherein the data acquisition and analysis means includes a system for analyzing and storing the data acquired by the NDI probes.

58. The surface scanner as defined in claim **57**, wherein the data acquisition and analysis system includes both hardware and software subsystems.

59. The surface scanner as defined in claim **58**, wherein the data acquisition and analysis hardware subsystem includes a host computer.

60. The surface scanner as defined in claim **59**, wherein the computer is portable.

61. The surface scanner as defined in claim **59**, wherein the computer includes an Intel 486 DX2/66 MHz microprocessor.

62. The surface scanner as defined in claim **59**, wherein the computer includes 64 Mb of RAM.

63. The surface scanner as defined in claim **59**, wherein the data acquisition and analysis system includes an uninterruptible power supply.

64. The surface scanner as defined in claim **59**, wherein the computer includes an outer chassis.

65. The surface scanner as defined in claim **64**, wherein the chassis houses a keyboard.

66. The surface scanner as defined in claim **65**, wherein the chassis supports a visual display for displaying the acquired and processed data from said data acquisition and analysis means.

67. The surface scanner as defined in claim **66**, wherein the visual display is a VGA monitor.

68. The surface scanner as defined in claim **67**, wherein the VGA monitor is a color monitor.

69. The surface scanner as defined in claim **64**, wherein the chassis supports a pointing device.

70. The surface scanner as defined in claim **64**, wherein the chassis includes ports for connecting to external devices.

71. The surface scanner as defined in claim **64**, wherein the chassis includes ports for connecting to external devices.

72. The surface scanner as defined in claim **64**, wherein the chassis supports a connection for a joystick.

73. The surface scanner as defined in claim **64**, wherein the chassis supports a data storage means for storing said data.

74. The surface scanner as defined in claim **73**, wherein the data storage means is a floppy disk drive.

75. The surface scanner as defined in claim **73**, wherein the data storage means is an internal storage device.

76. The surface scanner as defined in claim **73**, wherein the data storage means is a combination of an external storage device and an internal storage device.

77. The surface scanner as defined in claim **6**, wherein the internal and external storage devices includes a 1.44 Mb 3.5 floppy disk drive in combination with a 500 Mb internal hard drive, and an external 1 Gb read/write optical drive.

78. The surface scanner as defined in claim **57**, wherein the data acquisition and analysis means further cooperates with the scan control means, including a scan control system, for controlling the movement of the scanner.

79. The surface scanner as defined in claim **78**, wherein the scan control system includes a scan control board.

80. The surface scanner as defined in claim **79**, wherein the scan control board is a multi-axis controller, controlling movement of the first tractor assembly, the second tractor assembly, the third tractor assembly and the thruster assembly.

81. The surface scanner as defined in claim **80**, wherein the scan control system includes software for controlling the function of the scan control board.

82. The surface scanner as defined in claim **81**, wherein a scan pattern of the scanner is preprogrammed.

83. The surface scanner as defined in claim **82**, wherein the scan pattern is programmed using a teach-and-learn technique for inputting data points that define the overall scan area and shape.

84. The surface scanner as defined in claim **82**, wherein the scan pattern is programmed using a global coordinate system which permits referencing data points using identical coordinate systems laid-out on the actual surface to be inspected and the display of the scanned image.

85. The surface scanner as defined in claim **57**, wherein the data acquisition and analysis means further includes an ultrasonic board for processing ultrasonic data.

86. The surface scanner as defined in claim **57**, wherein the data acquisition and analysis means further includes a hardware subsystem having an eddy current board for processing eddy current data.

87. The surface scanner as defined in claim **57**, wherein the data acquisition and analysis means further includes a software subsystem having software files for controlling scanner system operations.

88. The surface scanner as defined in claim **87**, wherein the software subsystem includes software for performing ultrasonic data processing and analysis.

89. The surface scanner as defined in claim **87**, wherein the software subsystem includes software for performing eddy current data processing and analysis.

90. The surface scanner as defined in claim **87**, wherein the software subsystem includes software for performing mechanical impedance data processing and analysis.

91. A surface scanner comprising:

- a first flexible track assembly supporting a first tractor assembly;
- a second flexible track assembly supporting a second tractor assembly;
- a third track assembly, one end thereof being supported by the first flexible track assembly and the opposite end being supported by the second flexible track assembly;
- a third tractor assembly supported by the third track assembly;
- a thruster assembly supported by the third tractor assembly;

one or more NDI probes supported by the thruster assembly for acquiring data concerning a surface to be inspected;

- a scan control system for moving the NDI probes over the surface to be inspected; and
- a data acquisition and analysis system for processing and analyzing the data acquired by the NDI probe.

92. The surface scanner as defined in claim **91**, wherein the scanner includes a couplant delivery system for delivering couplant fluid to the NDI probes.

93. The surface scanner as defined in claim **91**, wherein the NDI probes include ultrasonic, eddy current and mechanical impedance data probes.

94. The surface scanner as defined in claim **91**, wherein the data acquisition and analysis system includes hardware and software subsystems for controlling scanner functions.

95. The surface scanner as defined in claim **91**, wherein in the scan control system includes a global coordinate system for referencing data points on the surface under inspection and displaying an image correlated with said data points.

96. A method for installing a surface scanner comprising:

coupling a first track assembly onto a surface to be inspected;

drawing a vacuum pressure through vacuum cups supported by the first track assembly, creating a suction force adhering the vacuum cups to the surface;

coupling a first tractor assembly to the first track assembly;

coupling a second track assembly onto a surface to be inspected such that first track assembly is offset from the second track assembly;

drawing a vacuum pressure through vacuum cups supported by the second track assembly, creating a suction force adhering the vacuum cups to the surface;

coupling a second tractor assembly to the second track assembly;

coupling a third track assembly to the first track assembly and the second track assembly such that the third track assembly spans the gap between the first track assembly and the second track assembly;

coupling a third tractor assembly to the third track assembly;

coupling a thruster to the third tractor assembly, wherein the thruster supports NDI probes; and

controlling movement of said NDI probes over at least a portion of a surface to be scanned to acquire data from said NDI probes related to said scan.

97. The method of installing a surface scanner as defined in claim **96**, wherein the step of controlling movement further includes step of an external data acquisition and analysis for controlling scanner functions.

98. The method of installing a surface scanner as defined in claim **97**, wherein the step of data acquisition and analysis includes software for defining a global coordinate system for referencing a point on the surface inspected to an identical point on a corresponding scanned image.

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US006378387B1

(12) **United States Patent**
Froom

(10) **Patent No.: US 6,378,387 B1**
(45) **Date of Patent: Apr. 30, 2002**

(54) **NON-DESTRUCTIVE INSPECTION, TESTING AND EVALUATION SYSTEM FOR INTACT AIRCRAFT AND COMPONENTS AND METHOD THEREFORE**

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(73) Assignee: **Aerobotics, Inc.**, Orangevale, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/645,540**

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(52) **U.S. Cl.** **73/865.8**
(58) **Field of Search** 73/1.79, 1.81, 73/588, 598, 600, 583, 865.8; 378/58, 62, 64; 701/29, 30, 32, 33, 35

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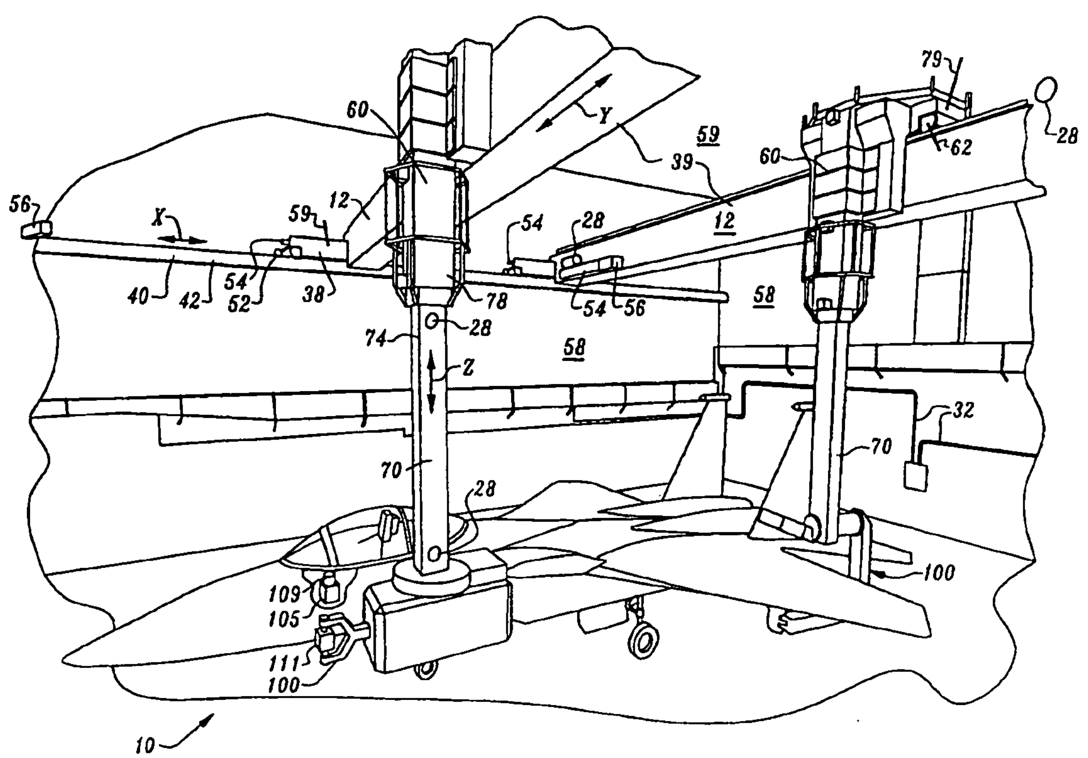
Primary Examiner—Robert Raevis
(74) *Attorney, Agent, or Firm*—Bernhard Kreten

(57) **ABSTRACT**

A non-destructive inspection, testing and evaluation system and process is provided for the review of aircraft components. The system provides for a structure configured to contain an inspection and testing apparatus and the aircraft components under inspection. The structure is lined with shielding to attenuate the emission of radiation to the outside of the structure and has corbels therein to support the components that constitute the inspection and testing apparatus. The inspection and testing apparatus is coupled to the structure, resulting in the formation of a gantry for supporting a carriage and a mast is mounted on the carriage. The inspection and testing equipment is mounted on the mast which forms, in part, at least one radiographic inspection robot capable of precise positioning over large ranges of motion. The carriage is coupled to the mast for supporting and allowing translation of the equipment mounted on the mast. The mast is configured to provide yaw movement to the equipment.

16 Claims, 11 Drawing Sheets



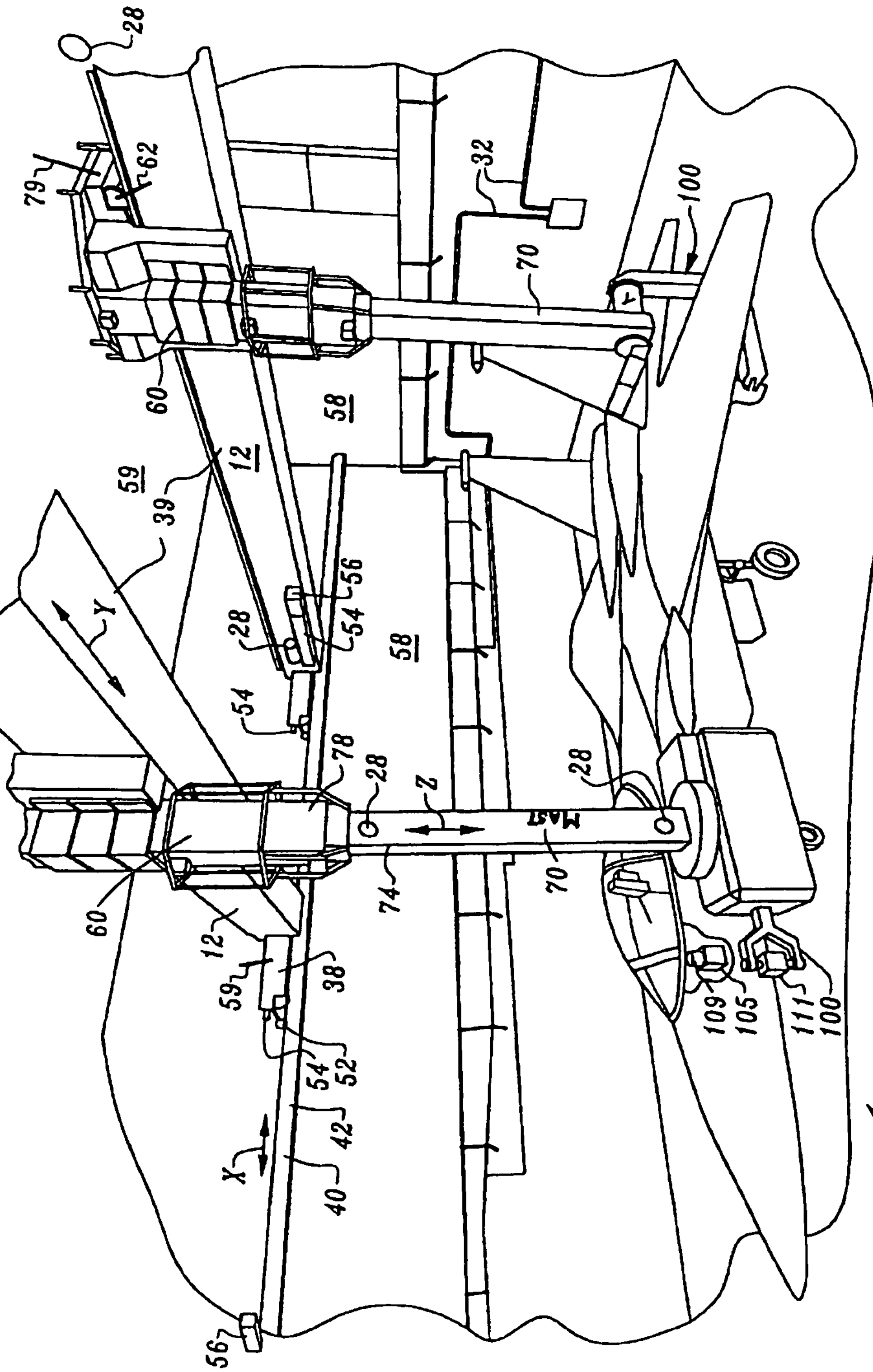

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Fig. 1

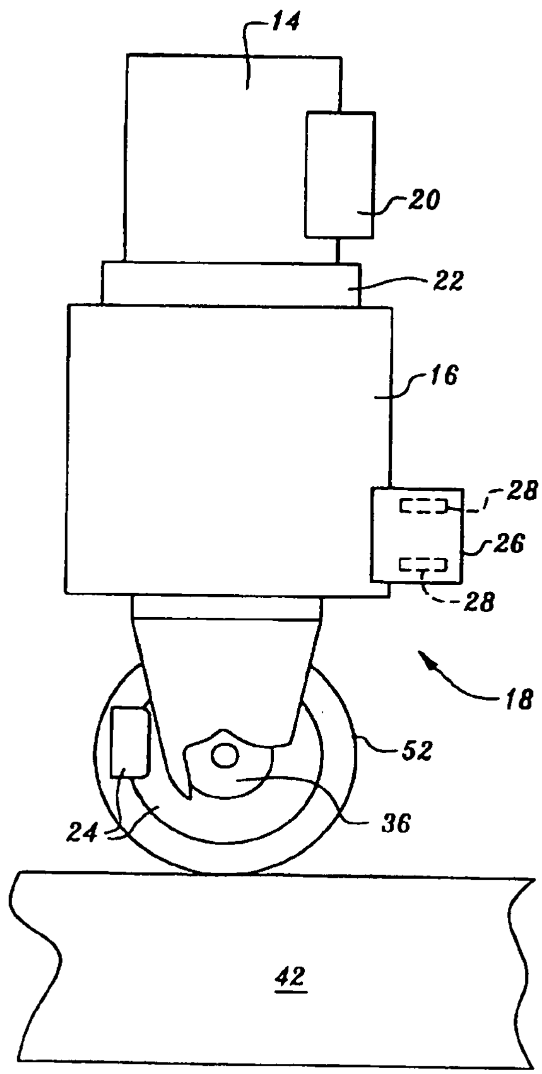

Fig. 1A

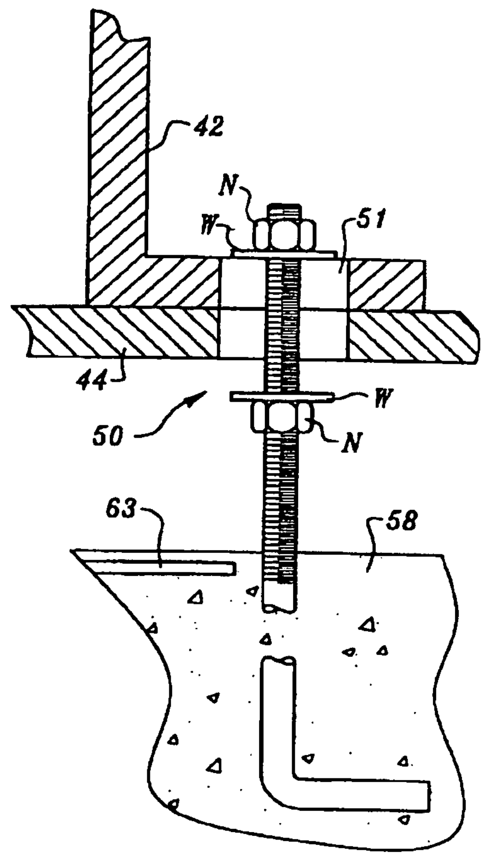

Fig. 2A

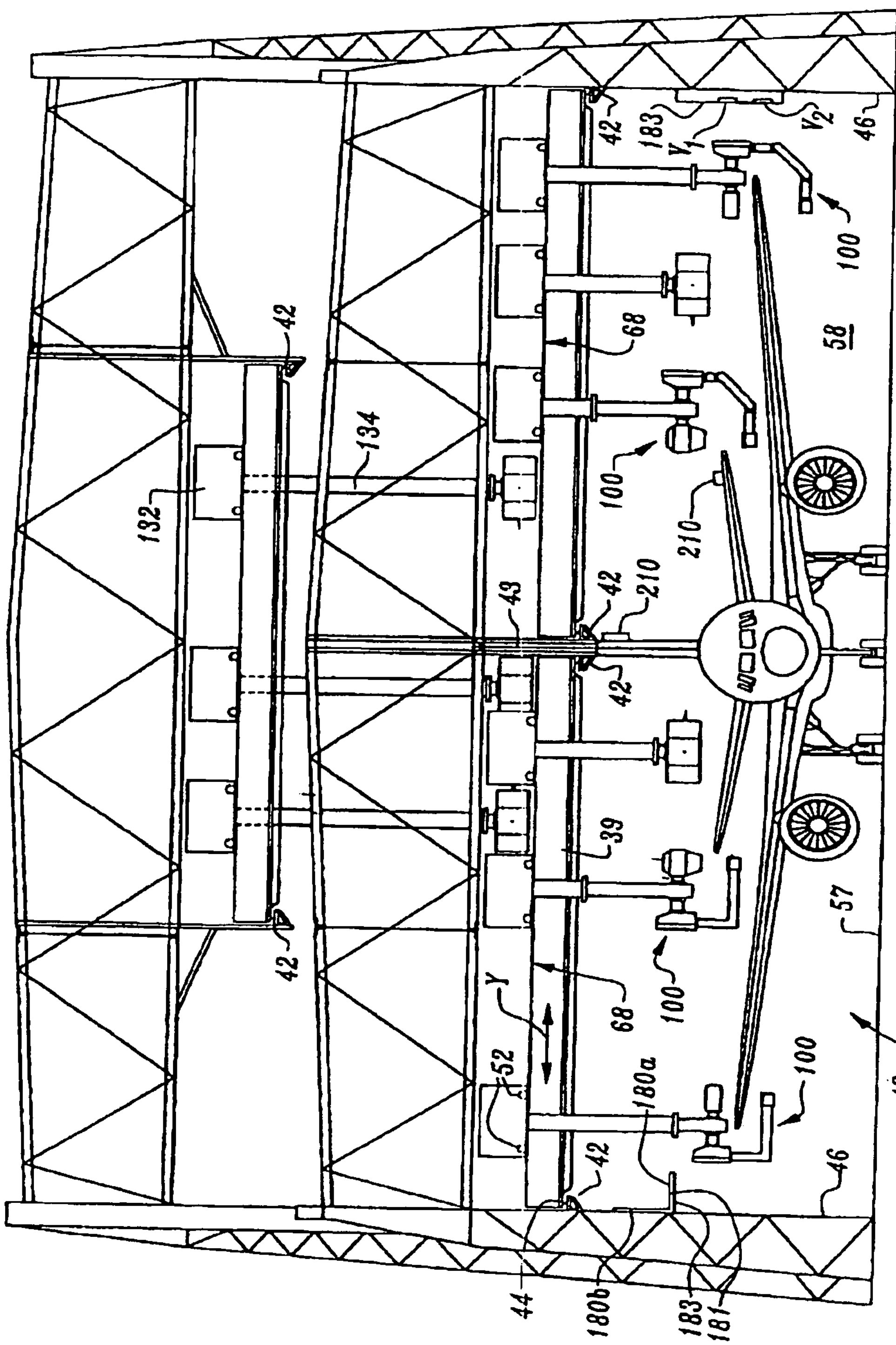
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Fig. 2

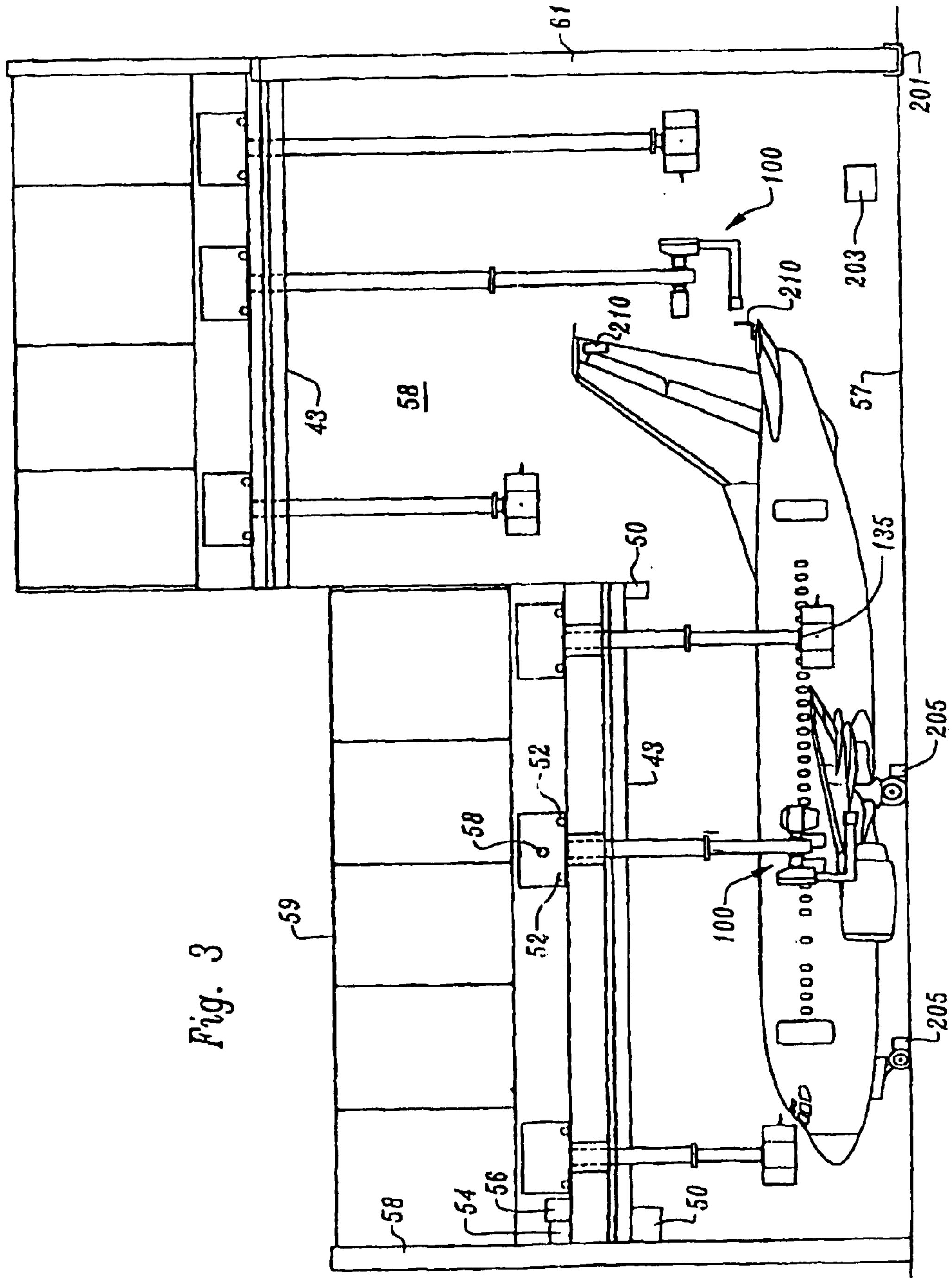
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Fig. 3

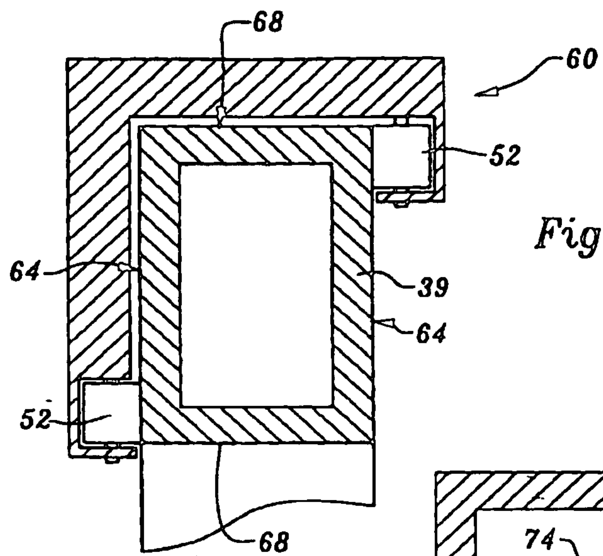


Fig. 3A

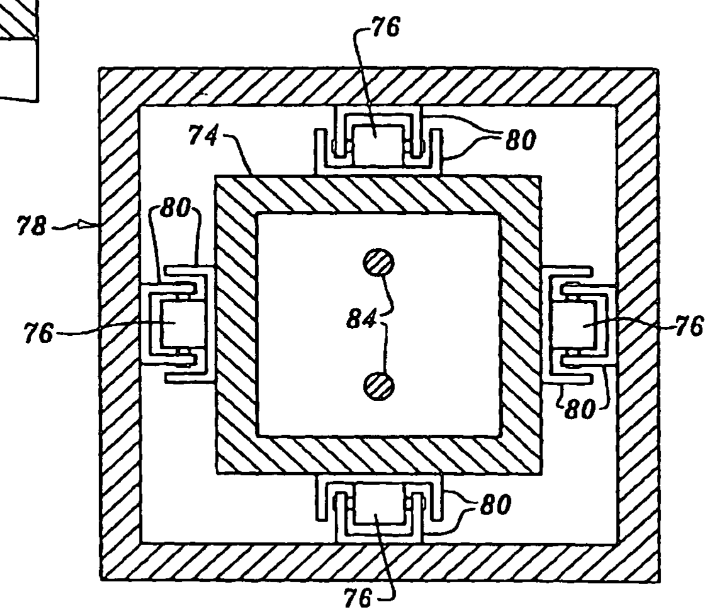


Fig. 4A

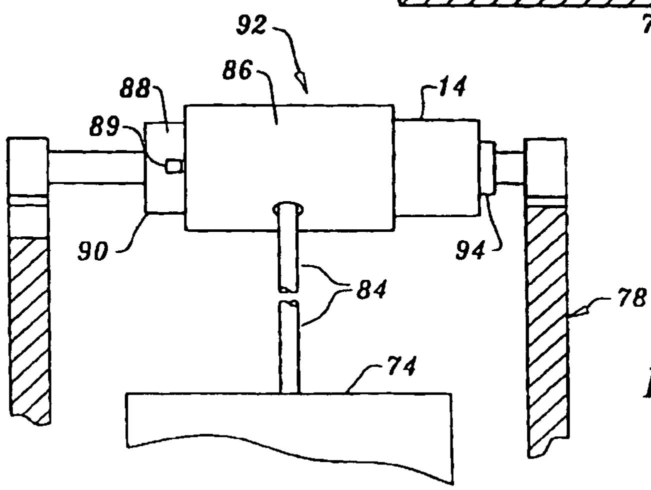


Fig. 5A

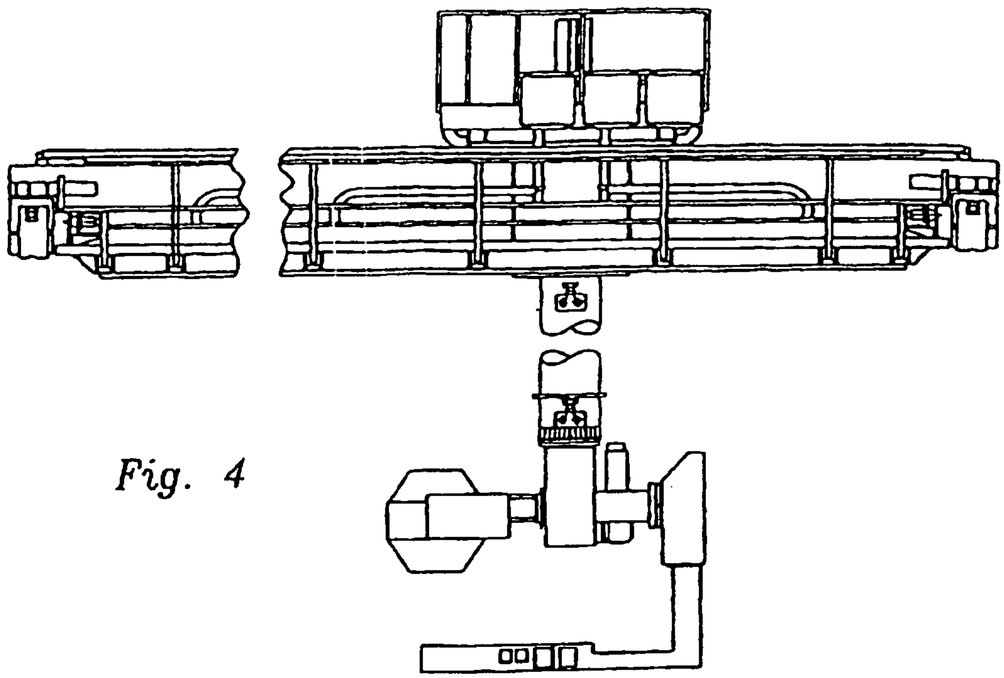


Fig. 4

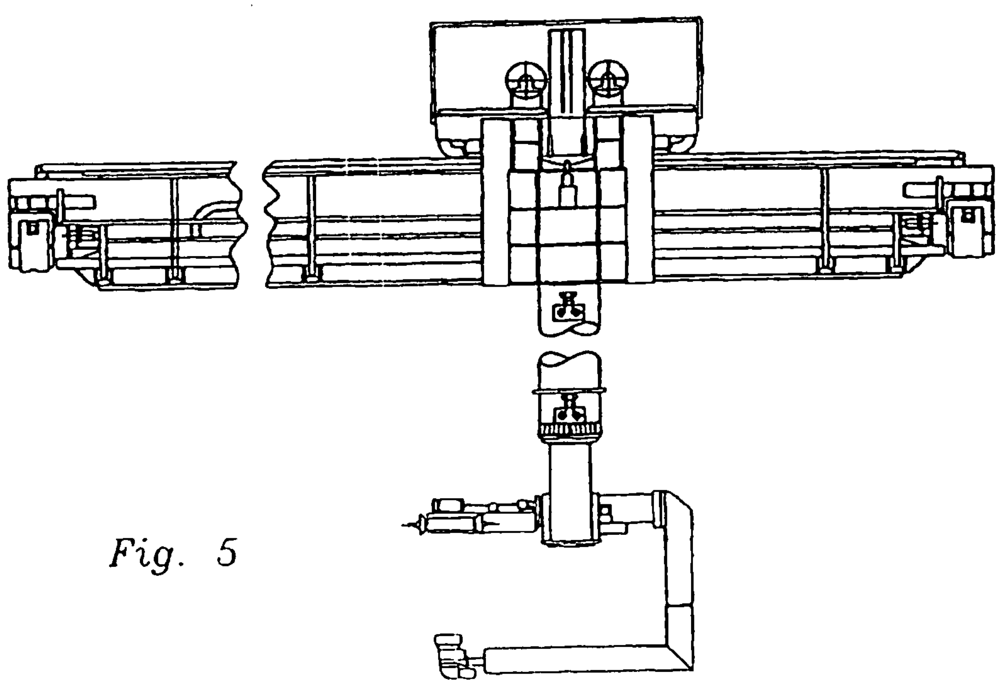
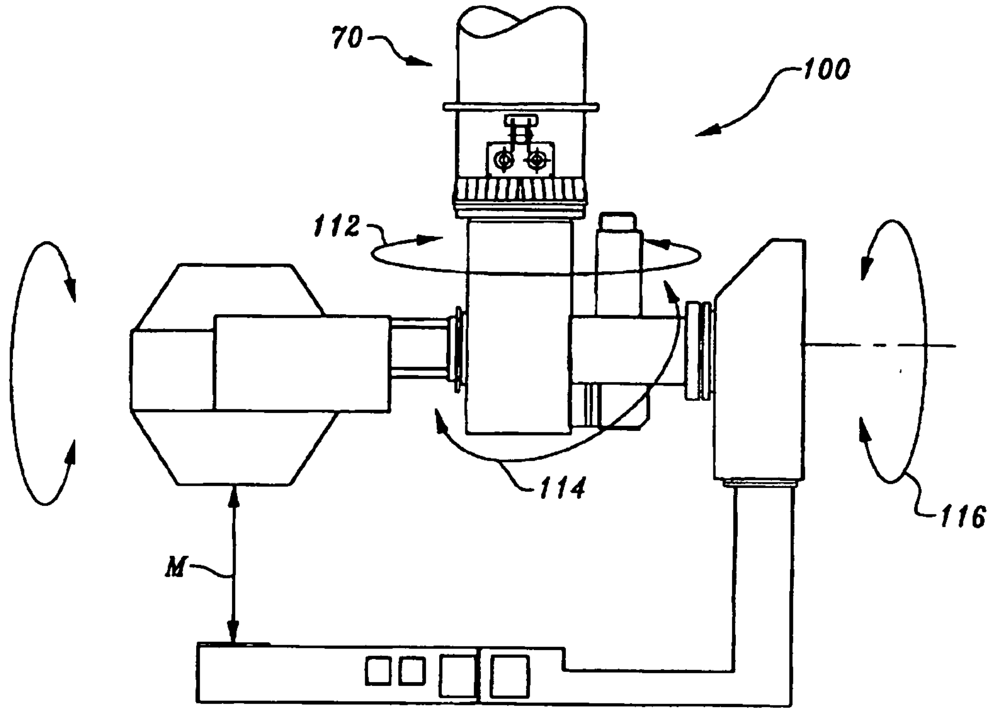


Fig. 5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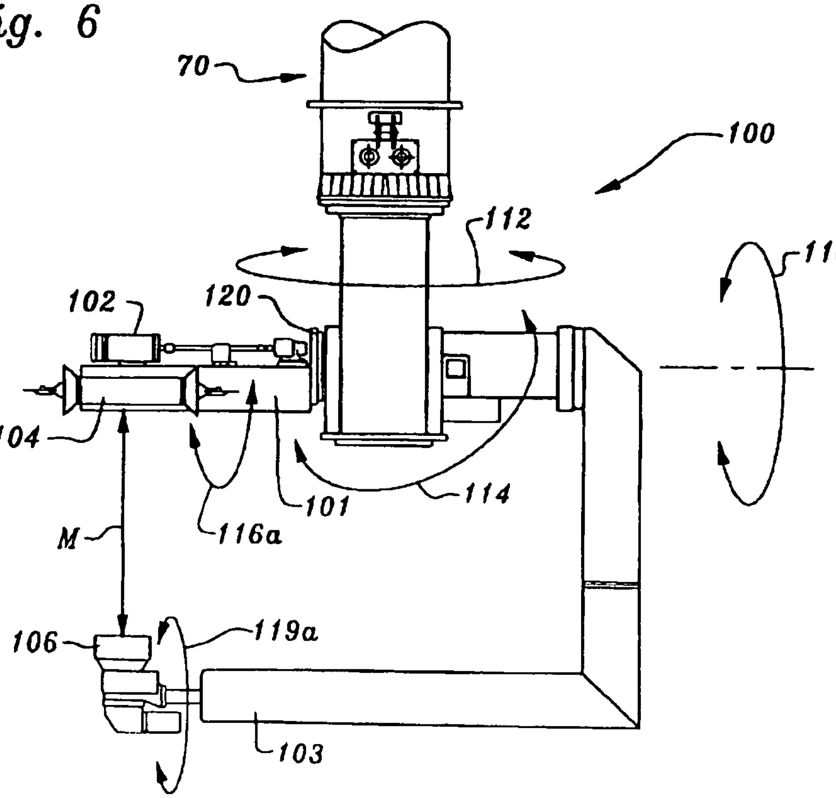
112
114
116
M

Fig. 6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119a
103

Fig. 7

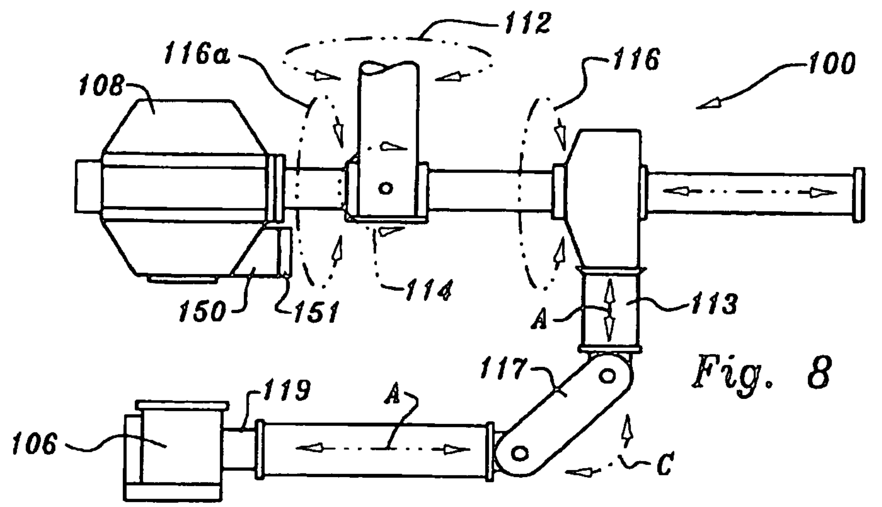


Fig. 8

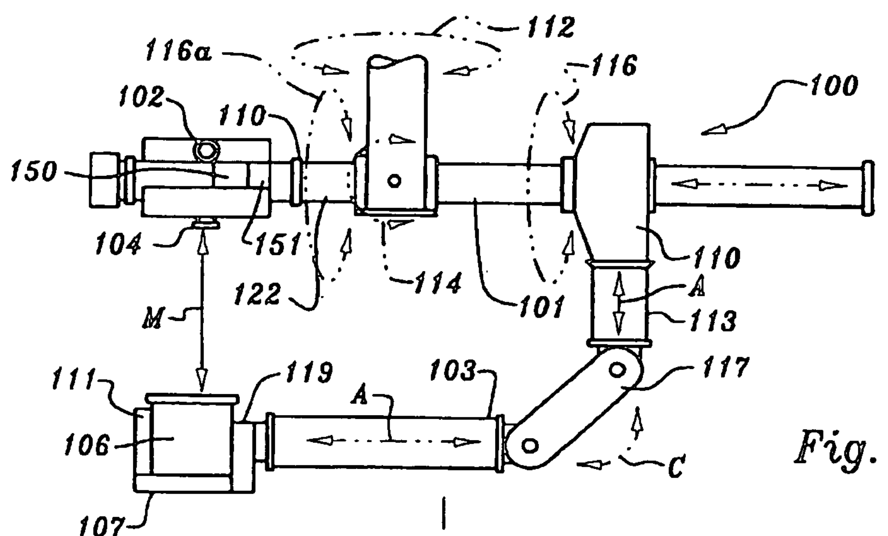


Fig. 9

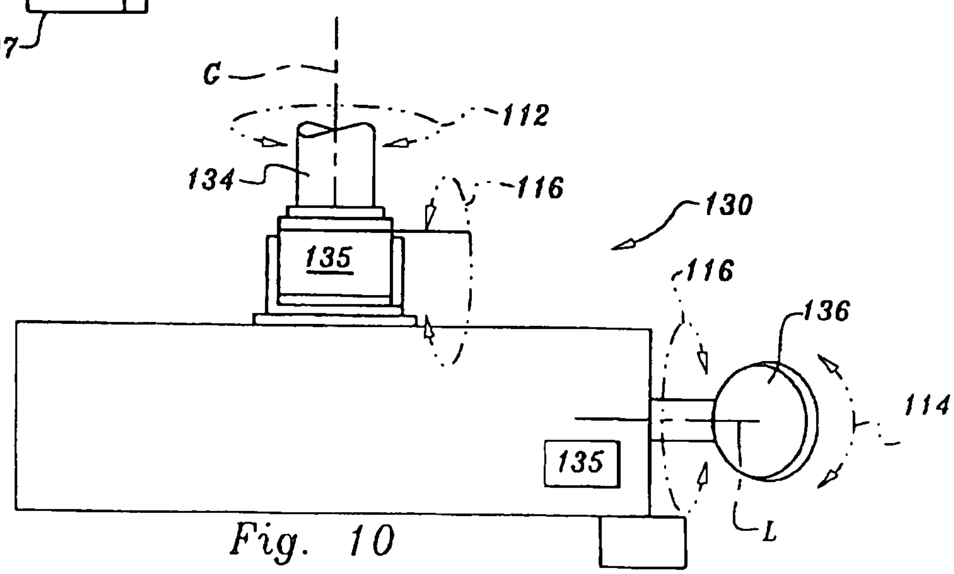


Fig. 10

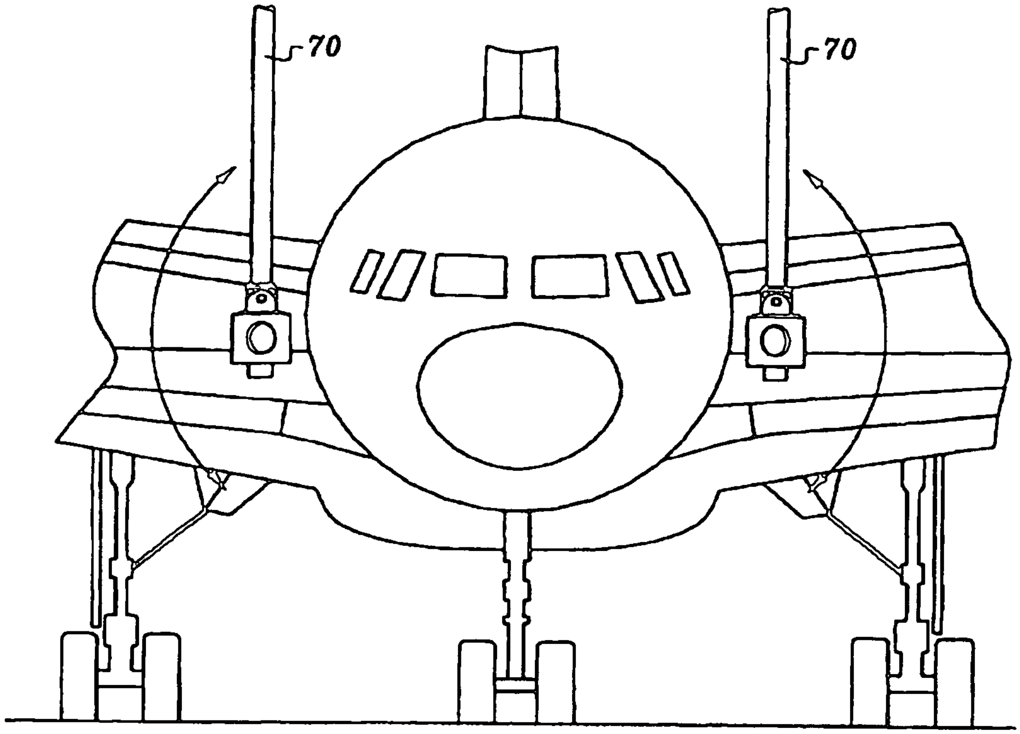


Fig. 11

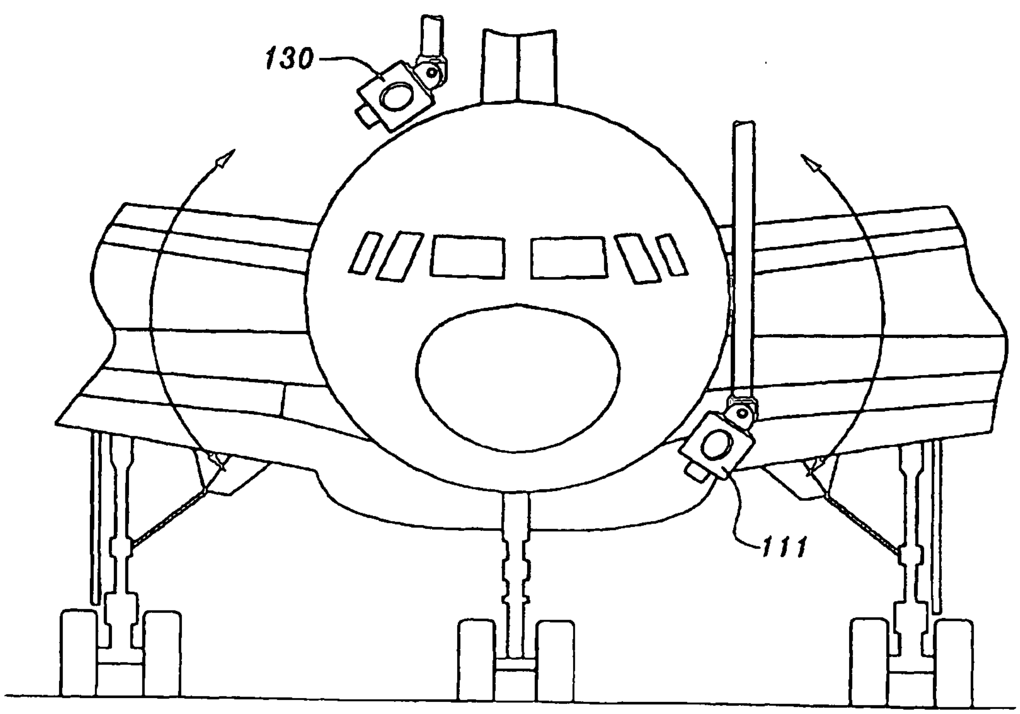
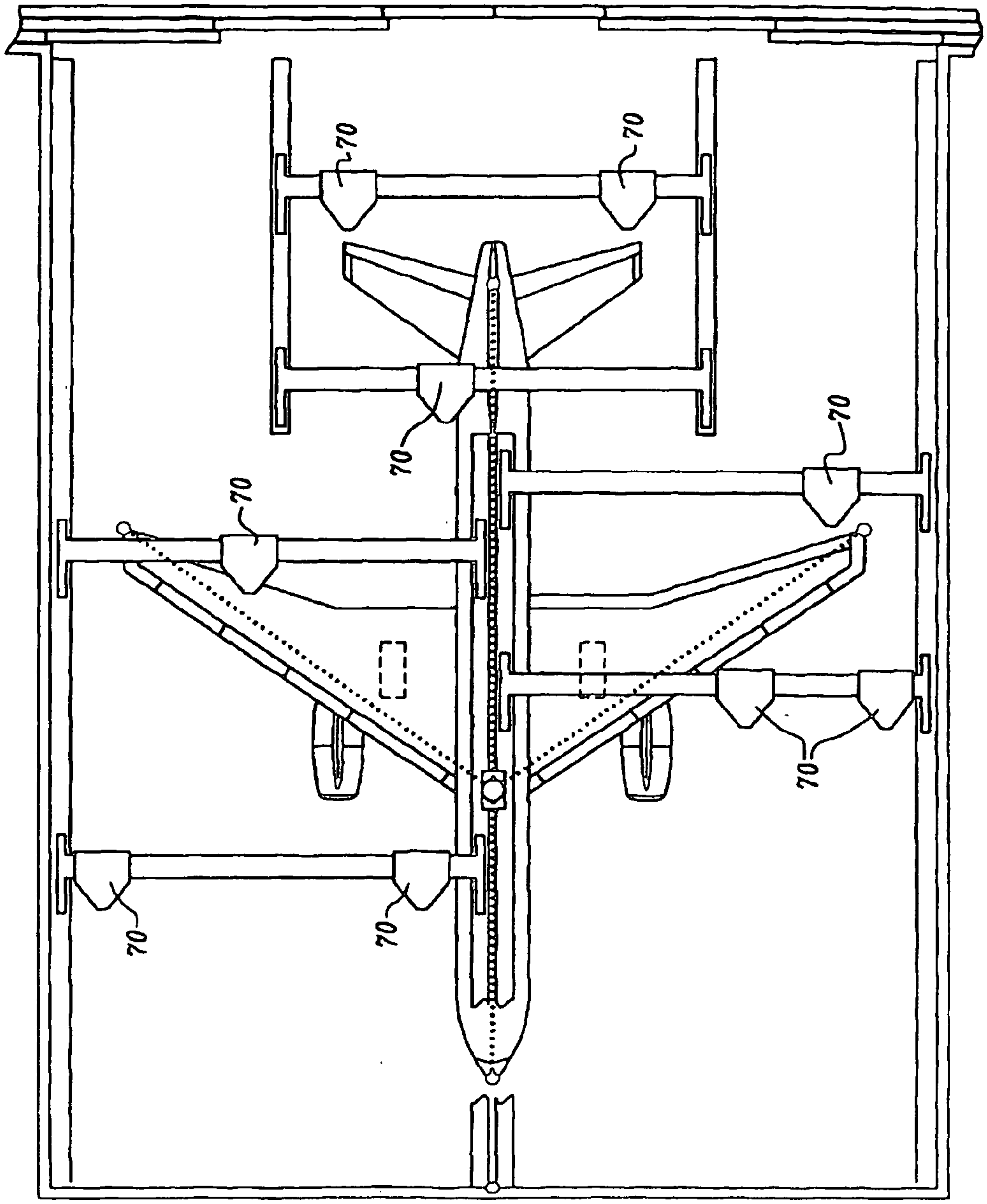


Fig. 12

Fig. 13



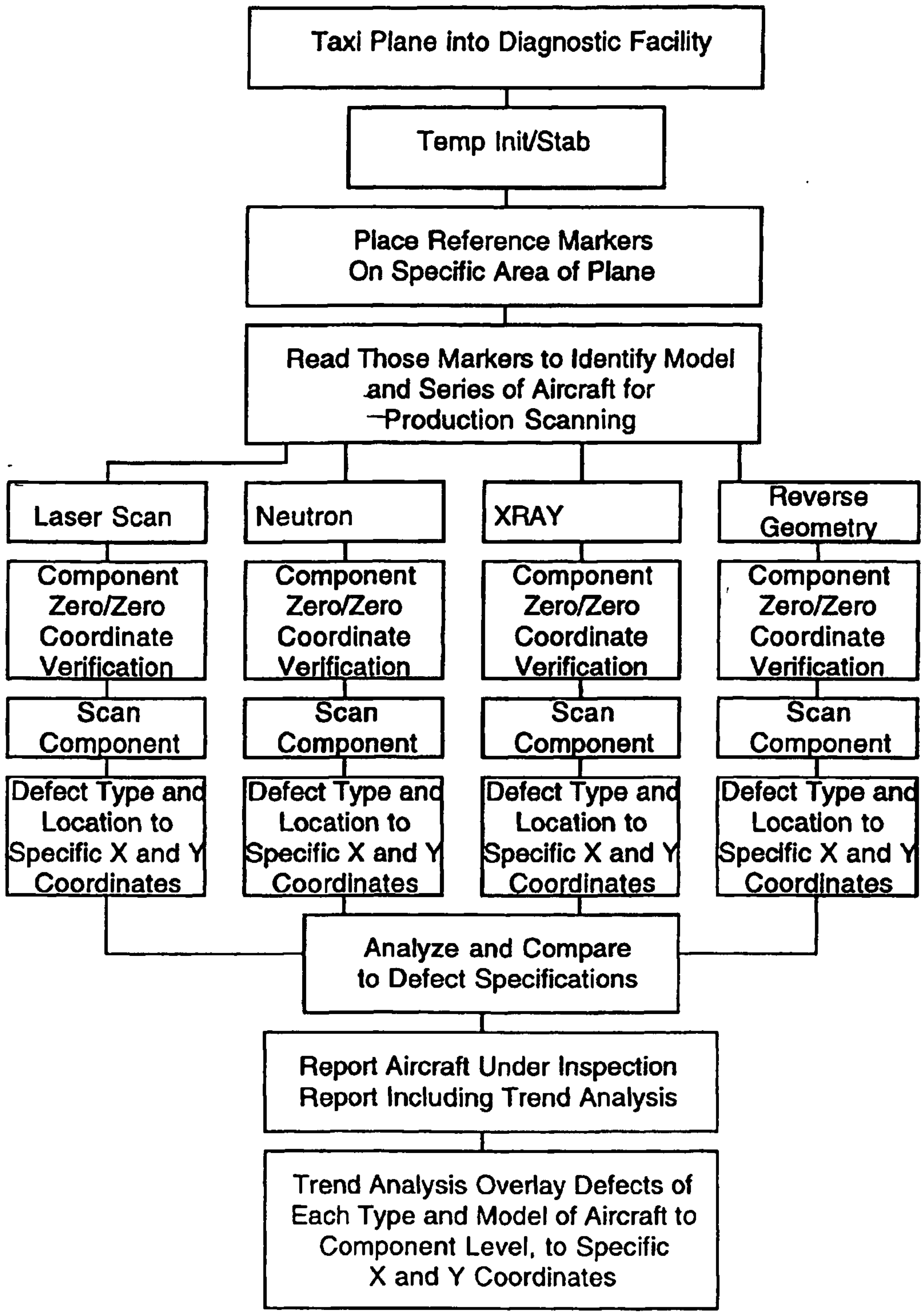

Taxi Plane into Diagnostic Facility
Temp Init/Stab
Place Reference Markers On Specific Area of Plane
Read Those Markers to Identify Model and Series of Aircraft for Production Scanning
Laser Scan
Neutron
XRAY
Reverse Geometry
Component Zero/Zero Coordinate Verification
Scan Component
Defect Type and Location to Specific X and Y Coordinates
Analyze and Compare to Defect Specifications
Report Aircraft Under Inspection Report Including Trend Analysis
Trend Analysis Overlay Defects of Each Type and Model of Aircraft to Component Level, to Specific X and Y Coordinates

Figure 14

NON-DESTRUCTIVE INSPECTION, TESTING AND EVALUATION SYSTEM FOR INTACT AIRCRAFT AND COMPONENTS AND METHOD THEREFORE

This invention was made in the performance of a cooperative research and development agreement with the Department of the Air Force. This invention may be manufactured and used by or for the Government of the United States for all government purposes without the payment of any royalty.

FIELD OF THE INVENTION

The following invention is generally related to instrumentalities and methodologies for the non-destructive inspection, and especially for testing and evaluation of aircraft components.

BACKGROUND OF THE INVENTION

Recent tragedies in aircraft transportation has caused concern over the ability of airlines to evaluate the airworthiness of aircraft within their respective fleets. As airframes age, the characteristics of the materials that constitute the airframe components change due to the stresses and strains associated with flights and landings. The material goes beyond the point of elasticity (the point the material returns to its original condition) and into the point of plasticizing or worse, beyond to failure. As a result, inspections and testing are conducted on aircraft components periodically during the aircraft's component life cycle as are mandated by governing bodies and based largely on empirical evidence.

Currently commercial industry inspection and repair method are inefficient, costly and not standardized. Their inspection and repair procedures and processes have changed little in the past 20 or 30 years and have not solved the "Aging Aircraft" safety problems. Inspection of aircraft components are historically limited to the "Tap Test," visual inspection, and Eddy Current analysis. Standardized technical repairs are nonexistent. Commercial safety integrity is continually compromised by not determining the extent of aircraft structure corrosion and fatigue.

Unfortunately, manned inspection is still the state of the art. Inspection timetables are developed and updated primarily as a function of anecdotal evidence, all too frequently based on airline catastrophes.

Inspections and testing are bificurated into two areas: destructive testing and nondestructive inspection (NDI), nondestructive testing (NDT) or nondestructive evaluation (NDE). The area of destructive testing, as the name implies, requires the aircraft component under scrutiny to be destroyed in order to determine the quality of that aircraft component. This can result in a costly endeavor because the aircraft component is destroyed even though it passed the test procedure. It is, therefore, no longer available for use. Frequently, where destructive testing is done on samples (e.g. coupons) and not on actual components, the destructive test may or may not be reflective of the forces that the actual component could or would withstand within the flight envelope of the aircraft.

On the other hand, NDI, NDT or NDE have the obvious advantage of being applicable to actual aircraft components in their actual environment. Several important methods of NDI, NDT or NDE that are performed in a laboratory setting are listed and summarized below.

Radiography. This is a general term for the inspection of a material by subjecting it to penetrating irradiation. X-rays

are the most familiar type of radiation used in this technique, although good damage detection has been done using neutron radiation. Most materials used in aircraft component manufacturing are readily acceptable to X-rays. In some instances, an opaque penetrant is needed to detect many defects. Real-time X-rays are starting to be used to permit viewing the area of scrutiny while doing the procedure. Some improvement in resolution has been achieved by using a stereovision technique where the X-rays are emitted from dual devices which are offset by about 15°. When viewed together, these dual images give a three-dimensional view of the material. Still, the accuracy of X-rays is generally no better than ±10% void content. Neutrons (N-ray), however, can detect void contents in the ±1% range. The difficulty is the obvious problem with safety and radiation sources. In addition to the normal use to detect internal flaws in the metals and composite structures, X-rays and neutrons can detect misalignment of honeycomb cores after curing.

Ultrasonics. This is most common method for detecting flaws in composite materials. The method is performed by scanning the material with ultrasonic energy while monitoring the reflected energy for attenuation (diminishing) of the signal. The detection of the flaws is somewhat frequency-dependent and the frequency range and scanning method most often employed is called C-scan. In this method, water is used as a coupling agent between the sending device and the sample. Therefore, the sample is either immersed in water or water is sprayed between the signal the signal transmitter and the sample. This method is effective in detecting defects even in thick samples, and may be used to provide a thickness profile. C-scan accuracies can be in the ±1% range for void content. A slightly modified method call L-scan can detect stiffness of the sample by using the wave speed, but requires that the sample density be known.

Acousto-ultrasonics. This analysis method is similar to ultrasound except that separate sensors are used to send the signal and other sensors are used to receive the signal. Both sensors are, however, located on the same side of the sample so a reflected signal is detected. This method is more quantitative and portable than standard ultrasound.

Acoustic emission. In this method, the sounds emitted by a sample are detected as the sample is subjected to a stress. The stress can be mechanical, but need not be. In actual practice, in fact, thermal stresses are the most commonly employed. Quantitative interpretation is not yet possible except for well-documented and simple shapes (such as cylindrical pressure vessels).

Thermography. This method, which is sometimes call IR thermography, detects differences in the relative temperatures of the surface and, because these temperature differences are affected by internal flaws, can indicate the location of those flaws. If the internal flaws are small or far removed from the surface, however, they may not be detected. Two modes of operation are possible-active and passive. In the active mode, the sample is subjected to a stress (usually mechanical and often vibrational) and then the emitted heat is detected. In the passive mode, the sample is externally heated and the thermal gradients are detected.

Optical holography. The use of laser photography to give three-dimensional pictures is call holography. This method can detect flaws in samples by employing a double-image method where two pictures are taken with an induced stress in the sample between the times of the pictures. This method has had limited acceptance because of the need to isolate the camera and sample from vibrations. Phase locking may eliminate this problem. The stresses that are imposed on the

sample are usually thermal. If a microwave source of stress is used, moisture content of the sample can be detected. For composite material, this method is especially useful for detecting debonds in thick honeycomb and foam sandwich constructions. A related method is called shearography. In this method, a laser is used with the same double exposure technique as in holography with a stress applied between exposures. However, in this case an image-shearing camera is used in which signals from the two images are superimposed to give interference and thereby reveal the strains in the samples. Because strains are detected, the size of the pattern can give an indication of the stresses concentrated in the area and, therefore, a quantitative appraisal of the severity defect is possible. This attribute, plus the greater mobility of this method over holography, and the ability to stress with mechanical, thermal, and other methods, has given this method wide acceptance since its introduction.

Even though there are a wealth of diagnostic tools, there is a need to provide systems and principled processes to execute NDI, NDT and NDE of aircraft and their constituent components to take advantage of the methods briefly described above in order to better characterize the material properties of materials used in the manufacturing of aircraft components. The present invention fulfills this need outside of a laboratory setting.

The present invention includes three robotic imaging inspection methods and technologies: real-time X-ray, N-ray and laser ultrasonics. When used separately, certain imaging inspection methods find certain aircraft structural defects. For example, the present invention's N-ray imaging inspection methodology locates corrosion and measurable loss of structural material. The present invention's real-time X-ray imaging inspection methodology can find the smallest of structural cracks; while the ultrasonics methodology locates defect regardless of a composite or metal structure's configuration. When used in combination on any given aircraft or component, all structural defects and discrepancies can be located within high precision and trend analysis of future defect problems per model and series aircraft can be formulated and determined.

The following citations reflects the state of the art of which applicant is aware and is included herewith to discharge applicant's acknowledged duty to disclose relevant prior art. It is stipulated, however, that none of these citations teach singly nor render obvious when considered in any conceivable combination the nexus of the instant invention as disclosed in greater detail hereinafter and as particularly claimed.

U.S. PAT. NO.	ISSUE DATE	INVENTOR
6,003,808	December 21, 1999	Nguyen, et al.
5,111,402	May 5, 1992	Brooks, et al.

SUMMARY OF THE INVENTION

The present invention is directed to systems and processes that perform NDI, NDT and NDE on aircraft in whole and for components individually. One key to the present invention involves systematic, automated inspection coupled with comparison to a standard.

The term "aircraft components" encompasses, but not limited to: items as small as individual fasteners, pieces, sections or strands of wiring, materials, fasteners once installed and in their environment, weld seams, sections of panels, mounts and brackets, control surfaces, landing gear, the components and pieces thereof; flight surfaces, components and pieces thereof; a powerplant, its sections, its components and pieces thereof; sections of a fuselage and its entirety; to the whole aircraft positioned in an inspection bay or hangar.

NDI, NDT or NDE systems and processes having the characteristics of the present invention constitute a structure, preferably configured as an enclosure, to contain an inspection and testing apparatus and the aircraft components under inspection. The structure is lined with shielding to attenuate the emission of radiation to the outside of the enclosure and having corbels therein to support the components that constitute the inspection and testing apparatus. The inspection and testing apparatus is coupled to the structure, resulting in the formation of a gantry for supporting a carriage and a mast mounted on the carriage. An electromagnetic radiation emitter, electromagnetic radiation detector or both are mounted on the mast which forms, in part, at least one radiographic inspection robot capable of precise positioning over large ranges of motion. The carriage is coupled to the mast for supporting and allowing translation of the at least one electromagnetic radiation emitter and detector mounted on the mast, wherein the mast is configured to provide two axes movement of the electromagnetic radiation emitter, detector or both.

The emitter, detector or both is configured to provide rotation about at least one axis of pitch, roll and yaw motion of the emitter, detector or both.

Such NDI, NDT or NDE systems and process are preferably configured wherein the emitter, detector or both are configured as a yoke to provide rotation about at least one axis of pitch and roll motion of the emitter, detector or both. The yoke could include first and second members capable of adjusting the distance between the members; whereby the first member supports a source of electromagnetic radiation and the second member supports at least one of an electromagnetic radiation detector or an imaging device.

An NDI, NDT or NDE system or process having the characteristics of the present invention preferably contains the steps to perform the method for the non-destructive inspection and testing of aircraft components including a database comprising at least one profile of a prototypical aircraft component, maintaining an enclosure at constant environmental conditions, placing at least one aircraft component into the enclosure and allowing sufficient time to permit the aircraft component to reach the constant environmental conditions, precisely placing reference markers on specific areas of the aircraft component, reading the location of the reference markers, comparing the reading with the at least one profile and reporting the resultant of the comparison. The reference markers introduce the aircraft to the system and can uncover gross distortions in the aircraft's geometry, and aircraft location.

Further characteristics of the present invention include a gantry robot having a yoke to which an attached scanning apparatus provides the capability to reposition the yoke and scanning apparatus without the need for disassembly. The joints of the yokes are configured so as to be capable of articulation such that each leg of the yoke may be raised or lowered. By allowing each leg of the yoke to be raised or lowered, the scanning apparatus may be used to scan areas of an intact aircraft that would otherwise be difficult or impossible to scan.

As previously stated the present invention has one or more robots. The use of multiple robots provides several

advantages. Firstly, multiple robots allow simultaneous inspection of several areas of an aircraft, thereby reducing the time required to inspect an aircraft. Secondly, multiple robots avoid the need for a single long supporting beam, which would reduce positioning accuracy and repeatability. Thirdly, multiple robots allow each robot to be specifically designed to inspect particular areas of an aircraft, thereby allowing accommodation of special attributes of the various areas.

A structure is provided to contain inspection apparatus and items under inspection and defines an enclosure. The structure comprises walls, a ceiling, and a floor. A hanger door entrance is defined in a wall. The hanger door entrance is equipped with a hanger door. The walls, ceiling, and hanger door are designed to attenuate x-ray radiation and neutron radiation.

Corbels are provided to support multiple robots. The walls, ceiling, and hanger door entrance are designed to support the corbels, which provide x-axis translation. The structure is designed to accommodate structural loading while maintaining accuracy and repeatability of robot position over six axes of movement within a narrow range of tolerances better than ±0.250 inches, and preferably better than ±0.160 inches. The structure accommodates structural loading of various types, for example floor loading, wind loading and loading from the mass of the robots.

One embodiment of the invention includes a plurality of carriages on a single beam. For example, one carriage may provide support and translation of a robot for n-ray radiography, and another carriage may provide support and translation for a robot for x-ray radiography.

The inspection facility is designed to protect personnel from radiation hazards (including X-rays and neutrons). Shielding, including shielding of walls, doors, and windows is provided. Interlocks are provided to prevent the emission of radiation when personnel might be endangered, such as when a door is opened. Other measures, such as key controls and password authentication are provided to prevent emission of radiation or other potentially hazardous activities, such as motion of robotic systems, without approval of authorized personnel. Radiation monitoring and alarm systems are provided to detect abnormal radiation levels and provide warning.

One example of a technique used to provide shielding is the penetration shielding areas (for example, walls, doors, floors, ceilings, windows, etc.) at an angle sufficient to ensure that any radiation substantially perpendicular to the plane of the shielding material will be incident upon the shielding material of which the shielding area is constructed. This technique avoids the need to add additional shielding material, such as by packing a perpendicularly bored hole with additional shielding material.

A method for design of a non-destructive inspection, testing and evaluation system for aircraft and components having a precision robotic system is provided. The dimensional and structural requirements of a building are determined, and a preliminary design for the building is made. The preliminary design for the building is analyzed to identify any frequencies at which such a building might resonate. For example, a technique such as finite element analysis may be employed. Based on the results of the analysis, the preliminary design of the building may be modified to correct any deficiencies.

The dimensional, structural, and functional requirements for robots to be housed within the building are determined, and a preliminary design of the robots is made. The preliminary design of the robots is analyzed to identify any frequencies at which such robots might resonate. Any interaction between the resonant frequencies of the building and the resonant frequencies of the robot are analyzed. Based on the results of the analysis, the preliminary design of either or both of the building and the robots may be modified to correct any deficiencies.

The dimensional, structural, and functional requirements of any end effectors mounted on the robots are determined, and a preliminary design of the end effectors is made. The preliminary design of the end effectors is analyzed to identify any frequencies at which such end effectors might resonate. Any interruption between other elements, such as the building or the robots, is analyzed. Based on the results of the analysis, the preliminary design of any or all of the building, robots, or end effectors may be modified to correct any deficiencies.

Another factor to be considered is the type of earthquake region in which the facility is to be located. Different earthquake regions may exhibit earthquakes having different characteristics, for example earthquakes having vibration and motion of predominantly a certain frequency range. This frequency range is determined for the location at which the facility is to be located based on geological data. The preliminary designs of the building, robots, and end effectors is analyzed base on anticipated excitation from earthquakes. Based on the results of the analysis, the preliminary design of any or all of the building, robots, or end effectors may be modified to correct any deficiencies.

When the preliminary designs of the buildings, robots, and end effectors are completed, modeling of the entire system may be performed to assure accuracy and repeatability of robot positioning. Oscillatory excitation of the system components resulting from robot motion and acceleration and deceleration may be analyzed. Designs of the system components may be modified to maximize desirable characteristics, such as accuracy and repeatability of robot positioning, while minimizing undesirable characteristics, such as unwanted oscillatory excitation of system components.

The major assemblies of the non-destructive inspection and testing structure are the structure itself, preferably a building and further defining an enclosure, and the inspection and testing apparatus. A structure is provided to contain the inspection and testing apparatus and the items under inspection or testing. The structure is preferably composed of walls, floor, a ceiling and a hanger door. The walls, ceiling and hanger door are designed to attenuate X-ray radiation and neutron radiation. Corbels are provided to support the multiple robots. The walls, ceiling and hanger door entrance are designed to support the corbels thus permitting translation across the items under inspecting, testing or evaluation. The structure is designed to accommodate structural loading while maintaining accuracy and repeatability of the robot positions, i.e., the inspection and testing apparatus over six axes of movement within a narrow range of tolerances better than plus or minus 0.25 inches and preferably better than plus or minus 0.16 inches. The structure accommodates structural loading of various types, for example, floor loading, wind loading and loading from the mass of the robot.

The non-destructive inspection and testing system for aircraft components is capable of precise positioning over large ranges of motion. The non-destructive inspection and testing system for aircraft components comprises a beam arrangement for supporting and allowing translation of a

carriage. The beam is mounted on rails which are attached to the facility corbels by the means of end trucks, providing movement along the length of the facility or X axes. The carriage moves along the length of the beam providing Y axes, and a telescoping tube or mast is attached to the carriage in a vertical position, providing Z axes. At the bottom of the mast, three axes of movement are provided, pitch, rotate, and yaw of the yoke to which the inspection apparatus is attached. The translations permit the system to scan the intact aircraft to the component level. The carriage is coupled to a mast structure for supporting and allowing translation of a yoke. The mast comprises a plurality of tubes that can move telescopically to provide a large range of motion in a vertical direction while supporting large amounts of mass. In one embodiment of the invention, the beam arrangement is located overhead, for example, near the ceiling of the building. The building and beam arrangement form a gantry for supporting the carriage and structure as well as the yoke which is mounted on the mast 40. In the preferred embodiment the yoke includes two members that may be extended for example telescopically to adjust the throat depth of the yoke. Also, one embodiment of the yoke is configured to accommodate surfaces that change the camber of the wing. In particular configurations the first member supports a beam source and the second member supports an imaging device. In an alternative embodiment the mast supports a laser ultrasonic scanner. This laser ultrasonic scanner is attached to the mast of the inspection and testing apparatus and configured with rotational axes to allow scanning in a plurality of directions across complex surfaces of the aircraft or aircraft components.

Real-time X-ray radiography is accomplished in motion utilizing multi-axis movement of robots to scan at the rate of one to three inches per second and at three to five times magnification. Any pendulum or sway effect at the bottom of mast (with yoke attached) causes the real-time radiography image to be un-focus, distorted and unreadable to the operator. The problematic pendulum or sway effect is caused by two separate resonating frequencies: the first is the fundamental frequency of the robot based upon the mass and rigidity of the robot structure; and the second is the robot mounting to the housing facility which has its own resonating frequency when the robot is in motion or multiple of robot in motion or work. Providing two separate parallel bridges mounted to single end trucks with carriage straddling both parallel bridges and the mast located between the two separate bridges yields acceptable results so long as the length of the bridge does not exceed a certain length, typically fifty feet. Providing a single rail bridge typically permits a length of the bridge not to exceed ninety-six feet.

Existing hangar structure would have to be modified or new facilities would have to be built to attenuate any pendulum effect and resonating frequencies that could distort robotic inspection readings. Facility modification or new design would be based upon three separate requirements: seismic; resonate frequency of the facility with the robots in motion and the robotic envelope. Site surveys would determine the seismic activity, ground water location, type of soil, soil compaction and would result in building the facilities foundation as an isolation pad. The resonate frequency of the facility with the robots in a static positions are modeled to evaluate the pendulum effect of the robots and to determine the amount of reinforcement of steel and concrete needed to meet frequency requirements for the facility's bearing walls. At issue is the facilities hangar door. As the robots are moved closer to the hangar door, the pendulum effects become unacceptable. Therefore, modification to the hangar door are needed to the effect of providing a steel and concrete header above the door; while, below the ground level provide a lateral tie or footer. Such modifications rigidify the side of the structure containing the hangar door to attenuate any resonate frequencies to acceptable levels for the inspection of aircraft with the robots. The robot envelope is determined by the type of aircraft that would be inspected within the facility. The envelope is factored in and any resonate frequencies are attenuated in order to provide inspection accuracy and repeatability.

Inspection of aircraft wings require the control surfaces to be extended to allow for a total wing inspection. This wing configuration causes sharp radial surface turns at the fore and aft ends of the wings' leading and trailing edge surfaces and the inability for a normal "C" shaped yoke to conform to these areas to perform a total inspection perpendicular to the part under inspection. The solution to this problem is to provide a modified "C" shaped yoke with the lower arm having an articulating member, akin to a double joint, in order to allow the lower arm to tuck underneath the control surface.

Further characteristics of the present invention include a gantry robot having a yoke to which an attached scanning apparatus provides the capability to reposition the yoke and scanning apparatus without the need for aircraft disassembly. The joints of the yoke are gimbaled, so as to be capable of articulation, such as each leg of the yoke allows both sender and receiver to maintain perpendicular alignment to each other. By allowing each leg of the yoke to be raised or lowered, the scanning apparatus may be extended, used to scan areas of an intact aircraft that would otherwise be difficult or impossible to scan. Yoke configuration also includes telescoping legs to allow the throat depth to change. This change in depth is needed to reach points on an aircraft's wing where the wing root may exceed 27 feet and where the outer part of the wing is approximately four feet across.

OBJECTS OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a new, novel and useful Non-Destructive Inspection, Testing and Evaluation System for Intact Aircraft and Components and method therefore.

It is a further object of this invention to provide a method and apparatus as characterized above which accurately forecasts the need for corrective measures in a timely manner.

It is a further object of this invention to provide a method and apparatus which is easy to use and minimize the need for highly experienced personnel.

It is a further object of this invention to provide a method and apparatus where the diagnosis is repeatable.

It is a further object of this invention to provide a method and apparatus where the system and method can be reliably replicated.

It is a further object of this invention to provide a method and apparatus where the results from individual inspectors can be subsequently incorporated into a trend analysis data base.

It is a further object of this invention to provide a method and apparatus where the analysis does not mandate destruction of the item examined.

These and other objects will be made manifest when considering the following detailed specification when taken in conjunction with the appended drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of the system according to the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

Considering the drawings, wherein like reference numerals denote like parts throughout the various drawing figures, reference numeral 10 is directed to the non-destructive inspection and testing system for aircraft components according to the present invention.

The Robotic Overhead Positioner (ROP), (e.g., FIG. 1) is a gantry robot that resembles an overhead crane. The ROP allows movement in three linear directions (X, Y, and Z) and three rotational directions (Yaw, Pitch and Roll to be described). Generally, to move in each of these directions, it uses a variable-speed DC motor 14 (FIG. 1A), a gearbox 16, and a drive mechanism 18 having wheels 52. Power to turn the motor (thus moving the robot) is supplied by a controller 20. Each motor 14 has an encoder 22, which tells the controller 20 the distance of travel; and it also has a solenoid energized electric disc brake 24, which keeps the robot in a frozen position whenever the controller 20 is not supplying power to the motor 14. For each direction the robot 12 can move, there is also an absolute-positioning resolver 26, which tells the controller 20 where the robot is via the encoder 22. Limit switches 28 inside the resolver 26 prevent the motors 14 from driving the wheeled drive mechanism 18 beyond its end of travel. Power to the motors 14 and signals to the controller 20 are supplied via cables 32 (FIG. 1), which are fully insulated and which have military-standard connectors. Heavy-duty frictionless bearings 36 are used throughout to maximize system reliability.

Specifically, in the first linear direction (X-axis) (FIG. 1 and FIG. 1A) the bridge 38 moves on the runway 40. The runway 40 is made of sets of two parallel rails 42 (FIG. 2) mounted on rail ledges 44 (FIG. 2A). FIG. 2 shows one rail 42 on each sidewall 46 (and two rails 42 on the central corbel 43) of the Inspection Bay 48; these rails 42 have adjusters 50 for leveling and parallel alignment. Please see FIG. 2A.

The wheels 52 support bridge end trucks 38, a pair of wheels 52 on each end, and ride on the rails 42. Each pair of wheels has its own motor 14 and its own resolver 26. The bridge 38 encloses and supports the drive mechanism 18. As the motors 14 turn, the wheels 52 turn, moving the bridge 38 back and forth on the rails 42. The dual motor 14/resolver 26 scheme enables the controller 20 to avoid the bridge 38 skewing off the rail 42. If the limit switches 28 in the resolver 26 were to fail, thereby allowing the operator to move the bridge 38 to the very end of the rails 42, shock absorbers 54 on the bridge 38 and end-stops 56 on the rails 42 prevent the bridge 38 from striking the walls 58. A crank 59 is provided on each end of the bridge 38 as a manual backup motion system to allow the bridge to move without the motor 14.

FIGS. 1 and 2 show the second linear direction (Y-axis) where the trolley 60 moves along a span 39 which extends between two rails 42. Similar to the X direction, a trolley 60 moves along span 39 in depending relationship. Please see FIG. 3A. The span 39 is box-shaped and has spaced parallel vertical rails 64 and spaced parallel horizontal rails 68 forming an enclosed box. The weight of the trolley 60 is bearing on its wheels 52 that ride on opposed outer faces of each vertical rail 64. As the motor 14 turns, the wheels 52 turn, moving the trolley 60 left and right (Y axis) on the span 39. One wheel set 52 rides on a lower edge of one vertical rail 64 and another wheel set 52 rides on a top edge of opposite vertical rail 64 to keep the trolley 60 (and thus the mast 70) from tilting. The span 39 preferably has an upwardly projecting central crown 68 (FIG. 2) of about one-half inch when unloaded and bows one-half inch downwardly when the trolley 60 moves to the middle of the span 39. Thus, the span 39 is therefore normalized (i.e., level) along the length. If the limit switches 28 in the resolver 26 were to fail, allowing the operator to move the trolley 60 to the end of the rails 42, shock absorbers 54 on the span 39 and end-stops 56 on the span's ends prevent the trolley 60 from striking the walls 58. A crank 62 is provided on each trolley 60 as a manual backup system to allow reorientation of the trolley 60 along span 39. The trolley's drive is similar to that shown in FIG. 1A.

The third linear direction (Z-axis) moves the mast 70 on the trolley 60 up and down via positioner 92, please see FIG. 5A. The mast 70 is preferably capable of hoisting at least 5000 pounds, and is designed such that the failure of any single part of the system will not cause its sensor array (to be described) at the free end of the mast 70 to fall to the bottom of mast travel. As seen in FIG. 4A, the mast 70 is a box-shaped inner telescoping tube 74 with wheels 76 on an inner surface of box-shaped outer tube 78 riding on rails 80 on the inner tube 74. As seen in FIGS. 4A and 5A, the mast 70 is hoisted by dual cables 84 and has two drums 86 (only one shown); as the motor 14 turns, each drum 86 deploys a cable 84, hoisting the inner tube 74. Each drum 86 has a brake 88 mounted to its drive shaft 89 to prevent the tube 74 from falling if one brake 88 should fail. A load sensing mechanism 90 embodied as an overload clutch is provided on the hoisting system brake 88 to stop the mast if a sensor supporting yoke 100 (e.g., FIG. 2) should catch on an object as it is hoisted up or down or if there is a system overload. This load sensing mechanism 90 will also stop the positioner 92 when one component of the hoist system quits operating. For a backup system, each cable/drum system is capable of hoisting the mast at full load. If the hoist were to over-speed, another sensor 94, monitoring amperage would again perform to trigger an emergency stop. A crank 79 (FIG. 1) is provided on each mast 70 as a manual backup motion system.

Three rotational axes are incorporated into each inspection yoke 100. Please see FIGS. 6 through 9. The yoke 100 is a C-shaped structure with an adjustable mouth M which spans the gap between the sources and receiver. Two X-ray sources 102, 104 (FIGS. 7 and 9), having differing outputs are mounted on the top support 101 of the yoke 100 and the image receiver 106 is mounted on the bottom by arm 103;

the yoke **100** also supports a collision-avoidance paneling **110**. The paneling is a pressure sensitive sheath and is mounted on all lower extremities of the mast **70**. The pressure sensitive paneling prevents gross contact with the aircraft by mandating a stop signal in the presence of a triggering pressure. During the scanning of the aircraft surfaces, the surface (e.g. wing) is positioned between the X-ray **102, 104** (and N-ray **108**, FIGS. **6** and **8**) sources and the imager **106**. A film source **107** may supplement or supplant the imager **106**.

The first rotational axis **112** (Yaw) rotates the inspection yoke **100** in a horizontal plane at the bottom of the mast **70**. The second rotational axis **114** (Pitch) pivots the inspection yoke **100** in a vertical plane at the bottom of the mast **70**. The third rotational axis **116** (Roll) rotates the inspection yoke **100** in a plane at the end of the pitch axis; this plane is oriented perpendicular to the pitch axis. Note X-ray **102, 104** and N-ray **108** can be independently rotated about **116**a. Further, each arm (e.g. bottom arm **103**, side arm) can change in length as shown by double ended arrows "A" in FIGS. **8** and **9**. Also note that link **117** connecting bottom and side arms **103, 113** can rotate about curved arrow "C" to adjust the dimension of adjustable mouth M, in conjunction with the telescoping arm's length along arrow "A".

The X-ray sources **102, 104** are mounted on a movable support to allow only one of the two sources to be aimed at the imager **106** at one time by rotation about ***116a***. This support, called a turret **120** (FIG. **7**), is rotated 90 degrees by a stepper motor **122** (shown schematically in FIG. **9**). Only the X-ray source aimed at the imager **106** may be activated unless a permanent record is desired via a film source **107** which rotates in the place of imager **106**. Alternatively, the film source **107** can rotate about axis **119** (arrow ***119a***, FIG. **7**) to orient the film source **107** to the X-ray **102, 104**. The X-ray sources **102, 104** are indexed into position as a function of the object being scanned, its thickness, and its composition (e.g. composition versus metal). The imager **106** is an image intensifier, which directs the X-ray image to the control room operator CRT screen. The bottom arm **103** may also carry another type of X-ray imaging system **111** for backscatter X-ray (reverse geometry X-ray). The sender unit **111** is shown mounted adjacent imager **106**. Photomultiplier tubes **109** (FIG. **1**) are positioned inside the aircraft to receive digital images from the sender **111**. Receivers **105** are also placed on the inside of the production aircraft structures and direct digital imaging information to be sent to the control room operators. Yoke manipulative and imaging capabilities specified for either the N ray or X ray could be incorporated in the other.

Because of the varying change in the thickness of aircraft internal structures (such as wings), the X-ray source output (KVP Kilovoltage Penetrating Power, MA Milliamps Current) is controlled by robotic coordinates to allow ramp up or ramp down of X-ray penetrating power. This allows clear and precise imaging. It also allows the operator to focus attention to the viewed images and not constantly adjusting output due to the change in the aircraft structure material thickness. More importantly, each and every aircraft is inspected exactly the same (standardization).

The yoke **100** also contains a heat gun **150**, somewhat like a hair dryer. This is used on both the X-ray and N-ray yokes to allow the operator to verify and distinguish the presence of moisture, water or fuel inside the aluminum or composite bonded structure. Current industry NDI or NDE methods cannot distinguish the difference between moisture and sealant. Once a defect area is detected by either the X-ray or N-ray inspection method, heat is applied by the yoke's heat gun **150** to that specific area. Heat out generation is monitored by an infrared pyrometer **151** in order not to exceed a limit, preferably 160 degrees F. on the structure where the heat is being applied. If moisture is present, the applied heat causes migration of the fluid away from the heat source due to expansion of the air within the heated structure area. Heat images are taken before and after heating. Alternate "before and after" images flash on the operator's CRT screen and image picture subtraction is accomplished. The difference allows the operator to watch moisture migration. This procedure is important in locating the water entry paths within the aircraft structure or component.

A laser ultrasonics apparatus, **130** is also mounted to the gantry robot system **12**. Like the yoke **100**, the apparatus **130** (FIG. **10**) is coupled a carriage **132** (FIG. **2**) and a mast **134** mounted to the carriage **132** with rotational axes as described for the previous trolley and mast. The ultrasonic laser apparatus **130** allows X (along line L), Y (up and down along line G), and rotational movement (e.g. about arrows **112, 114, 116**) by using stepper motors **135**. The rotational movement of the laser ultrasonic apparatus allows it to reach underside areas of the fuselage while being support by the gantry robot system **12** that is above the fuselage. Please see FIGS. **10, 11** and **12**. A mirror **136** receives laser energy L from within housing **130** and distributes the energy on the scanned surface by mirror rotation, indexing and mast rotation and scanning (FIG. **12**). Reflected laser light provides further diagnostics.

Each individual robot has a "home" position to verify accuracy and to correct possible relocated robot movement (such as from earthquakes). An example of this is the home position fixture for the X-ray and N-ray inspection system. The home position fixture is preferably inverted "L" shape flat plate steel **180** (FIG. **2**) whose vertical leg ***180b*** is attached to the wall **46** with approximately four feet overhang provided by horizontal leg ***180a*** from the wall. The flat steel plate overhang horizontal leg ***180a*** is parallel to the concrete facility floor. A small 0.030-inch hole **181** is drilled through the center of the overhang plate ***180a***. With the X-ray system on, the operator CRT screen contains crosshairs (like a hunting rifle scope) to locate the crosshairs in the center of the overhang 0.030-inch hole at 5× geometric magnification. This provides a home position initialization step (calibration) and is preferably performed prior to each and every aircraft inspection and also for all robots and each inspection method (X-ray, N-ray and Laser Ultrasonics). Laser alignment relies on a uniform thickness plate **183** having at least two variations V_1 and V_2 from the uniform thickness at known locations. The laser when scanning the variations (e.g. a counter-bore) should reflect the known variations as a function of relative length and distance. In FIG. **2A**, rails **42** can be aligned by oval slots **51** allowing motion of rail **42** relative to its support plate **44**. A J bolt supports rail **42** and plate **44** in wall **58**. A threaded free end of J bolt **50** includes washers W and nuts N for vertical and lateral truing.

As previously stated, the present invention has at least one and preferably three or more robots. The use of multiple robots provides several advantages. Firstly, multiple robots allow simultaneous inspection of several areas of an aircraft, thereby reducing the time required to inspect an aircraft. Secondly, multiple robots avoid the need for a single long supporting beam, which would reduce positioning accuracy and repeatability. Thirdly, multiple robots allow each robot to be specifically designed to inspect particular areas of an aircraft, thereby allowing accommodation of special attributes of the various areas.

Corbels 12, 43 and rails 42 are provided to support multiple robots. The walls 58, ceiling 59, and hanger door entrance 61 are designed to support the corbels and rails, which permit linear translation. The location of the corbels within the structure, e.g., an aircraft hanger, is designed to accommodate structural loading (due to weight of the robot, robotic movement yielding unaccepted resonate frequencies, etc.) while maintaining accuracy and repeatability of robot position over six axes of movement within a narrow range of tolerances to ±0.160 inches. The structure accommodates structural loading of various types, for example floor loading, wind loading and loading from the mass of the robots.

The inspection facility is designed to protect personnel from radiation hazards (including X-rays and neutrons). Shielding 63 (FIG. 2A), including shielding of walls, doors, and windows is provided. Interlocks 201 (FIG. 3) are provided to prevent the emission of radiation when personnel might be endangered, such as when a door is opened. Other measures, such as key controls and password authentication are provided to prevent emission of radiation or other potentially hazardous activities, such as motion of robotic systems, without approval of authorized personnel. Radiation monitoring and alarm systems 203 are provided to detect abnormal radiation levels and provide warning.

One example of a technique used to provide radiation safety even though the walls, doors, ceiling and viewing windows are designed to accept maximum radiation at a distance of three feet, is not allowing the X-ray or N-ray sources to be aimed at these surfaces. The robot positioners only allow the radiation source to be aimed toward the concrete bay floor 57, or aircraft structure. This is accomplished by programming the robotic movement throughout the facility. Other than in the scan plan during the aircraft inspection operation, the radiation sources are non-operational. This is called the "Robotic Approach." Both X-ray and N-ray sources are on/off systems; neither source can be energized other than at the beginning of the scan plan inspection operation or calibration. Override of this radiation protection system is accomplished for robot or source maintenance purposes only and controlled by software code known only to the first level supervisor and maintenance personnel.

A method for design of a non-destructive inspection, testing and evaluation system for aircraft component having a precision robotic system is provided. The dimensional and structural requirements of a building are determined, and a preliminary design for the building is made. The preliminary design for the building is analyzed to identify any frequencies (earthquake zones) at which such a building might resonate. For example, a technique such as finite element frequency analysis may be employed. Based on the results of the analysis, the preliminary design of the building may be modified to correct any deficiencies.

The dimensional, structural, and functional requirements for robots to be housed within the building are determined, and a preliminary design of the robots is made. The preliminary design of the robots is analyzed to identify any frequencies at which such robots might resonate. Any interaction between the resonant frequencies of the building and the resonant frequencies of the robots are analyzed. Based on the results of the analysis, the preliminary design of either or both of the building and the robots may be modified to correct any deficiencies.

The dimensional, structural, and functional requirements of any end effectors mounted on the robots are determined, and a preliminary design of the end effectors is made. The preliminary design of the end effectors is analyzed to identify any frequencies at which such end effectors might resonate. Any interruption between other elements, such as the building or the robots, is analyzed. Based on the results of the analysis, the preliminary design of any or all of the building, robots, or end effectors may be modified to correct any deficiencies.

Another factor to be considered is the type of earthquake region in which the facility is to be located. Different earthquake regions may exhibit earthquakes having different characteristics, for example earthquakes have vibration and motion of predominantly a certain frequency range. This frequency range is determined for the location at which the facility is to be located based on geological data. The preliminary designs of the building, robots, and end effectors are analyzed base on anticipated excitation from earthquakes. Based on the results of the analysis, the preliminary design of any or all of the building, robots, or end effectors may be modified to correct any deficiencies.

When the preliminary designs of the buildings, robots, and end effectors are completed, modeling of the entire system may be performed to assure accuracy and repeatability of robot positioning. Oscillatory excitation of the system components resulting from robot motion and acceleration and deceleration may be analyzed. Designs of the system components may be modified to maximize desirable characteristics, such as accuracy and repeatability of robot positioning, while minimizing undesirable characteristics, such as unwanted oscillatory excitation of system components.

An NDI, NDT or NDE system or process having the characteristics of the present invention preferably contains the steps to perform the method for the non-destructive inspection and testing of aircraft intact or components including a database comprising at least one profile of a prototypical aircraft or component (a comparison standard), maintaining an enclosure at constant environmental conditions as to temperature, humidity, pressure, etc., and placing at least one aircraft or component into the enclosure for comparison with the standard.

A "gold body" database (i.e., a standard) is established for each configuration of aircraft such as the Boeing 727, 737 or 757. Also the length and height of the aircraft may vary and is identified by model and series such as the Boeing 737-100 or 737-400. Each model and series aircraft is located to a specific spot for the nose gear and main landing gear tires centerline and lined on the floor. Other production inspection aircraft of the same model and series will also use the line on the floor for rough positioning. The aircraft is then jacked into position using jacks 205 (FIG. 3) taking the load off of the tires and actuators. Thus, the aircraft becomes fixed in position and can no longer move due to tire pressure changing because of environmental changes or loss of hydraulic pressure in the actuators. Vision edges 210 (FIGS. 2 and 3), with two straight metal edges, 90 degrees to each other are attached to the aircraft's wing tips; horizontal stabilizer, outer leading edges and/or to other parts of the aircraft. The location of these vision edges are checked against the standard for initializing the system and to identify the type and model of aircraft to be inspected and also detect gross distortion and torsion of the airframe to be inspected. Thus, the vision edges define reference markers.

Each robotic imaging system such as the N-ray, X-ray and Laser Ultrasonics has a vision system, which allows the robot the ability to locate the aircraft within the robotic

envelope. Scan plans are taught to each robot. For example, the X-ray robot is taught the angle of attack to inspect the wing internal structure for cracks such as in the inspection of the wing ribs and spars or taught to inspect the bonded structure on the same wing such as the leading edge, spoilers or flaps. Each scan plan is broken down to the aircraft component or panel level. Each component or panel has its own beginning point for a particular scan. This is known at the zero-zero coordinates. Defects are noted within the component or panel to exact X and Y-axis part coordinates for follow-on repair purposes or for tracking the defect growth over time.

Scan plans are different for each robotic imaging method such as for N-ray, X-ray or Laser Ultrasonics because of the field of view and the area of interest due to the type of aircraft structure. Nonetheless, the X and Y-axis coordinates on the component or panel remains the same. This allows the results of each inspection method (X-ray, N-ray, Reverse Geometry and Laser Ultrasonics) to be identified on a master layout; over laying the results of the insertions to identify multi-site damage and to download the results of each aircraft inspected to overlay on the same component or panel for determining trend analysis and model aircraft fleet condition. Please see FIG. 14.

Once the whole aircraft has been taught to the system of the present invention, the scan plans of each NDI method can be applied in part or whole on follow-on aircraft to be inspected (production aircraft). Production aircraft are not absolutely required to be jacked in place for stabilization. The aircraft is located within the facility to the line markings on the floor plus or minus eight inches. The robot then seeks to locate the vision edges on the aircraft. Once located, the robot automatically recognizes where the taught aircraft was in reference and where follow-on production aircraft is located. This is called an offset and is transparent to the system operators. Scan plan accuracy is 0.160 thousands of an inch on all production aircraft. Because no two aircraft are exactly the same, the system operator can manually align the robot by joystick control to the beginning zero-zero coordinates on each and every component, allowing 0.160 thousands of accuracy of scan for each component from aircraft to aircraft.

Moreover, having thus described the invention, it should be apparent that numerous structural modifications and adaptations may be resorted to without departing from the scope and fair meaning of the instant invention as set forth hereinabove and as described hereinbelow by the claims.

I claim:

1. A method for the non-destructive inspection and testing of aircraft components, the steps including:

creating a database comprising at least one profile of a prototypical aircraft component;

maintaining an enclosure at constant environmental conditions;

placing at least one aircraft component into the enclosure;

allowing sufficient time to permit the aircraft component to reach the constant environmental conditions;

placing reference markers on specific areas of the aircraft component;

reading the location of the reference markers;

comparing said reading with said at least one profile;

reporting the resultant of said comparison.

2. The method of claim 1 further including configuring the aircraft component as an entire airplane;

placing the reference markers including locating the markers on the airplane's wing tips, horizontal stabilizer, and outer leading edge.

3. The method of claim 2 further including forming the markers as vision edges defined by two straight metal edges, 90 degrees to each other.

4. The method of claim 2 further including jacking the load off tires and actuators of the airplane to offset tire pressure and hydraulic pressure variation.

5. The method of claim 2 further including scanning portions of the airplane using a laser and developing laser data.

6. The method of claim 5 further including comparing developed data with a standard.

7. The method of claim 2 further including scanning portions of the airplane using neutron radiation and developing neutron radiation data.

8. The method of claim 7 further including comparing developed data with a standard.

9. The method of claim 2 further including scanning portions of the airplane using x-ray and developing x-ray data.

10. The method of claim 9 further including comparing developed data with a standard.

11. The method of claim 2 further including scanning portions of the airplane using reverse geometry and developing reverse geometry data.

12. The method of claim 11 further including comparing developed data with standard.

13. The method of claim 2 further scanning the airplane for anomalies against a standard and storing data derived during scanning as to location and airplane type.

14. The method of claim 13 further including comparing similar airplane types and their data to spot trends in the data.

15. The method of claim 13 further including placing the scanner on a support and moving the scanner in three linear directions and three rotational directions through the support.

16. The method of claim 15 further including scanning for anomalies in the integrity of the airplane without destroying the integrity.

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